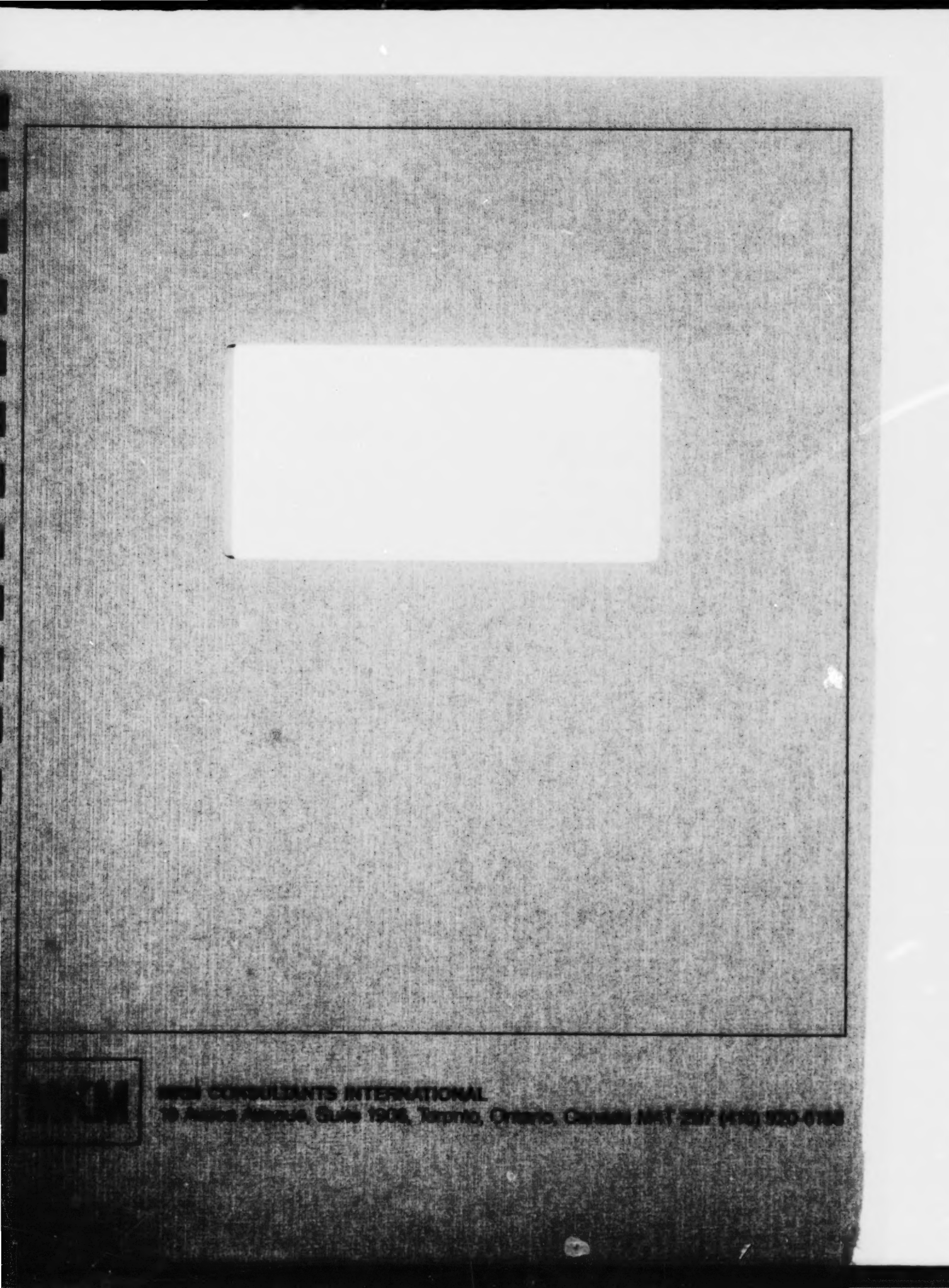


MPH CONSULTANTS INTERNATIONAL
10 Alcorn Avenue, Suite 1908, Toronto, Ontario, Canada M4T 2S7 (416) 920-0168

IMPACT OF DEVELOPMENTS IN ADVANCED CERAMICS

ON CANADIAN INDUSTRY

FINAL REPORT

VOLUME 2. BACKGROUND INFORMATION

Prepared by

M.K.Murthy
MKM Consultants International

for

CANMET - Mineral Sciences Division
Dept. of Energy, Mines and Resources
Ottawa, Ontario

DSS Contract File No: 06SQ.23440-7-9023
DSS Contract Serial No: 23440-7-9023/01-SQ

Scientific Authority: Dr.T.A. Wheat
Science Branch Contracting Officer: Dr.R.G. Agarwal

290 pp

MICROMEDIA

TABLE OF CONTENTS

Title	Page No
1. INTRODUCTION	1
2. OBJECTIVES	3
3. METHODOLOGY	3
4. STATUS OF ADVANCED CERAMICS	4
4.1 Definition and Classification	4
4.2 Properties of Advanced Ceramics	5
4.3 Classification	5
4.3.1 Advanced Structural Ceramics	7
4.3.2 Advanced Functional Ceramics	8
4.4 Status of Advanced Structural Ceramics	11
4.4.1 General	11
4.4.2 Status of Materials Technology and Applications	13
4.4.2.1 Non-oxide Ceramics	13
4.4.2.2 Oxide Ceramics	23
4.4.2.3 Composites	29
4.4.3 Status of Process and Manufacturing Technology	38
4.4.4 Status of Advanced Ceramic Powders	44
4.4.5 Sol-gel Technology	67
4.4.6 Status of Advanced Ceramic Coatings	70
4.5 Status of Advanced Functional Ceramics	82
4.5.1 General	82
4.5.2 Bioceramics and Ceramic Implants	82
4.5.3 Electronic Ceramics	82
4.5.3.1 Multilayer Circuits	89
4.5.3.2 Sensors	89
4.5.3.3 Integrated Optics	97
4.5.3.4 Ceramic Superconductors	97

5. MARKET AND COMMERCIAL STATUS 103

5.1 General 103
5.2 Market Data for Japan 103
5.3 Market Data for U.S. 115
5.4 Market Data for U.K. 117
5.5 Market Data for W.Europe 124
5.6 Market Data for World Consumption 124
5.7 Commercial Application Status of Advanced Structural Ceramics 127

5.7.1 Heat Engine Applications 127
5.7.2 Industrial Applications 134

5.7.2.1 Cutting Tools 134
5.7.2.2 Wear/Corrosion Parts 137
5.7.2.3 Heat Exchangers 149

6. INTERNATIONAL PERSPECTIVE 151

6.1 Japan 152
6.2 United States 156
6.3 France 165
6.4 W.Germany 171
6.5 United Kingdom 173
6.6 EEC 173

7. STATUS OF ADVANCED CERAMICS IN CANADA 174

7.1 Overview 174
7.2 Manufacturers of Advanced Ceramic Powders 176
7.3 Manufacturers of Electroceramics in Canada 180
7.4 Manufacturers of Advanced Structural Ceramics in Canada 185
7.5 Industrial Plasma Coating Facilities in Canada 197
7.6 R&D Capabilities in Canadian Universities 203
7.7 R&D Capabilities in Federal Government Laboratories. 203

7.7.1 CANMET - Dept.of Energy, Mines & Resources.... 203
7.7.2 National Research Council 207
7.7.3 Atomic Energy of Canada Limited 208

7.8 R&D Capabilities in the Provincial Research Organizations 209

7.8.1 Alberta Research Council 209
7.8.2 Manitoba Research Council 210
7.8.3 Nova Scotia Research Foundation Corporation .. 210
8.8.4 Ontario Research Foundation 211

7.9 Industry Associations 212

7.9.1 The Advanced Materials Technology Unit 212
7.9.2 The Canadian Advanced Industrial Materials Forum 213
7.9.3 The Canadian University-Industry Council on Advanced Ceramics 214
7.9.4 The Ontario Centre for Materials Research 215

8. IMPACT OF ADVANCED CERAMICS ON CANADIAN INDUSTRY SECTORS.... 216

8.1 General 216
8.2 Auto Parts Industry 219
8.3 Mining and Mineral Processing Industry 223
8.4 Pulp and Paper Industry 233
8.5 Oil & Gas and Petroleum Industry 241
8.6 Machinery and Equipment Industry 247
8.7 Advanced Ceramic Needs and Requirements of Canadian Industry 250

8.7.1 Needs of Hi-Tech Industries 250
8.7.2 Needs of Automotive and Aerospace Industries.. 250
8.7.3 Needs of Primary Industries 254

9. SUMMARY AND CONCLUSIONS..... 258

9.1 Summary 258
9.2 Conclusions 262

10. RECOMMENDATIONS 266

11. APPENDICES 269

Appendix 1. Bibliography 269

Appendix 2. List of Persons who Partcipated in Discussions.. 275

LIST OF TABLES

	Title	Page No
1.	Applications of Electronic Ceramics	10
2.	Typical Present and Projected Applications for Silicon Carbide Components	19
3.	Typical Present and Projected Applications for Silicon Nitride Ceramics	22
4.	Typical Present and Future Uses for Sialons	24
5.	Industrial Applications for Zirconia Ceramics	26
6.	Prototype Applications for Zirconia Toughened Alumina	28
7.	Typical Properties of Common Fibre Reinforcement Material for Ceramic Matrix Composites	32
8.	A Comparison of Fracture Tougheness and Critical Flaw Size Distribution of Monolithic and Composite Ceramics ...	33
9.	List of Manufacturers of Some Metal Matrix Composites Containing Advanced Ceramics Reinforcement	36
10.	Manufacturing Costs in High-Performance Materials	43
11.	Chemical Techniques Used in the Preparation of Advanced Ceramic Powders	45
12.	Economics of Advanced Ceramics Production	48
13.	List of Manufacturers of α-SiC and β-SiC Powders	50
14.	Properties and Characteristics of α-SiC Powders Manufactured by H.C.Starck Co, W.Germany	54
15.	Commercial Manufacturers and Suppliers of Silicon Nitride Powders	58
16.	Commercial Manufacturers and Suppliers of ZrO_2 Powders ...	63
17.	Properties of High Purity Alumina Powders Produced by Difference Processes	65

18. Commercial Manufacturers and Suppliers of High Purity Alumina Powders 66

19. Processes Used for the Production of Ceramic Coatings and for the Modification of Ceramic Surfaces 71

20. Characteristics and Properties of Ceramic Coatings Considered Desirable 72

21 Selected Substrate and Coating Materials 74

22 Wear Resistant CVD Coatings and Their Applications 76

23. Typical Applications for Plasma Sprayed Coatings 77

24. Biomaterials Market 83

25. Types of Ceramic Sensors 91

26. List of Pyroelectric Materials and Japanese Manufacturers 95

27. Projected Market Size for Infrared Sensors in Japan 96

28. Applications of Pyroelectric Devices 98

29. World Markets for Superconductors 102

30. Comparison of Market Projection Data for Advanced Ceramics in Japan 104

31. Market Data for Silicon Carbide, Silicon Nitride and Zirconia Ceramic Powders in Japan 108

32. Japanese Advanced Industrial Fine Ceramic Market Trends... 111

33. Sales Potentials for Advanced Industrial Fine Ceramics in Japan 112

34. Production and Sales of Fine Ceramics in Japan in February 1987 113

35. U.S. Shipments of Advanced Ceramics by End Use to the Year 2000 116

36. Sales of Advanced Ceramics in the U.S. 118

37. Market Value for Electronic Ceramic Products in the U.S... 119

38. U.S.Shipments of Advanced Ceramics (1980 - 1995) 120

39. U.S.Markets for Advanced Structural Ceramics 122

40. U.K. Consumption of Advanced Industrial Fine Ceramics 123

41. Worldwide Advanced Ceramics Sales by Region 126

42. List of Joint R&D Programs Between Japanese Auto Manufacturers and Ceramic Component Manufacturers 131

43. List of U.S. Manufacturers of Silicon Nitride and Sialon Products 141

44. List of European Manufacturers of Silicon Nitride and Sialon Products 143

45. List of Japanese Manufacturers of Silicon Nitride and Sialon Products 145

46. Estimated Consumption of Silicon Carbide by End-Use for the Western Industrialized Countries in 1982 147

47. List of World Manufacturers of Silicon Carbide Advanced Ceramics 148

48. Principal U.S. Federal Government Laboratories performing Advanced Ceramics Research and Development 158

49. U.S.Federal Government Programs on Advanced Ceramics 160

50. List of Members of the United States Advanced Ceramics Association (USACA) 164

51. Overview of French Industrial Activity in Advanced Ceramics 167

52. Automotive-Related and Other Advanced Ceramic R&D in France 169

53. Advanced Ceramics Research at French Institutes and Universities 170

54. Ceramic Engineering Educational Insitutions in W.Germany.. 172

55. Manufacturers of Advanced Ceramics Powders in Canada 177

56. Manufacturers of Advanced Electroceramics in Canada 181

57. Manufacturers of Advanced Structural Ceramics in Canada... 186

58. Industrial Plasma Coating Facilities in Canada 198

59. Canadian Universities Active in Advanced Ceramics 204

60. University Research Areas in Ceramics 205

61. Major Canadian Engine and Engine Parts Manufacturers 220

62. Metal Commodities and Non-Metallic Minerals Produced in Canada 225

63. Major Operating Mines in Canada 227

64. List of Pulp and Paper Mills in Canada (1987) 234

65. List of Operating Refineries in Canada (1987) 242

66. Typical Cutting Tool Materials and Their Applications 249

LIST OF FIGURES

	Title	Page No
1.	Relationships between Functions, Properties and Applications of Advanced Ceramics	6
2.	Different Types of Electronic Ceramics	9
3.	Relative Level of International Effort in the Development of Advanced Structural Ceramics	14
4.	Refel Process for the Manufacture of Silicon Carbide Advanced Ceramics	16
5.	Ceramic Production Processes Used in the Manufacture of Advanced Ceramics	39
6.	Typical Flow Sheet Representing the Processing Steps Used in Manufacturing -SiC Grains and Powders	51
7.	H.C.Starck Co., Process for the Manufacture of -Silicon Nitride Powders	53
8.	Schematic of the Process for the Manufacture of Silicon Nitride Powders by Carbothermic Process (Toshiba)	56
9.	Schematic of Process for Producing Silicon Nitride Powders from Silicon Tetrachloride and Ammonia	57
10.	Typical Syalon Ceramic Compositions	59
11.	Carbonate and Chloride Methods for Producing Pure Zirconia from Ores	62
12.	World Market for Ceramic Coatings by End Use Industries (1985)	78
13.	Commercial Status of Various Forms of Advanced Ceramics for Engines for the years 1975 - 2010	79
14.	Projected Growth Rate for Ceramic Coatings by End Use Industry, 1986- - 1995	81
15.	Electroceramics Market	84

16. Circuitry in Ceramic Materials for Use in Electronic Packages, Integrated Optics, Cooling Systems, Electromechanical Transducers, Magnetic Recording, Multilayer Actuators, Ionic Batteries, and Chemical Sensors 86

17. Ionic and Electronic Mechanisms Involved in Electroceramic Compositions 87

18. Integrated Ceramic Packages of the Future Incorporating Many Different Components 88

19. Typical Integrated Optic Processor based on Lithium Niobate Substrate 99

20. The Increase in Superconductivity Temperature from the Time of Its Discovery in 1911 101

21. Estimates of the Scale of the Advanced Ceramics (Fine Ceramics) Market in Japan (MITI) 105

22. Breakdown of Ceramic Powder sales in Japan According to Chemical Composition 107

23. Advanced Ceramics Markets by End-Use Applications for the Years 1990 - 2000 110

24. Distribution of Electroceramic Components Produced by Japanese Manufacturers 114

25. A Private Industry Projection of U.S. Market for Advanced Ceramics 121

26. Growth of Advanced Ceramics Market in Europe 125

27. Estimated Scenario for Implementation of Ceramic Components for Structural Application Categories 128

28. Trend Toward Increased Use of Advanced Structural Ceramics in Japanese Automobiles 132

29. Typical Wear/Abrasion Resistant Industrial Applications for Advanced Structural Ceramics 138

30. International Forces in Advanced Ceramics 153

31. Breakdown of Advanced Ceramics Industry in Japan by Sectors 155

32. Components of Gross Domestic Product of Canada (1986)..... 217

1. INTRODUCTION

It is now generally recognized that the future economic progress of industrialized countries is governed by the success with which the material needs of industry are met to satisfy technological needs. Without the best materials, leadership in any major field of technology is impossible. The capacity to develop and use advanced materials technologies is an important determinant of industrial competitiveness. The worldwide recognition of the economic potential of advanced materials technologies has been evident in a range of government policy initiatives and business activity. In addition to meeting the needs of industry, advanced materials are creating new opportunities and providing society with new ways to address such problems as the scarcity of resources and/or utilization of mineral resources for economic growth. Productivity and the structure of the labour force are also profundly affected by advances in materials technology. Advanced materials technologies, like other strategic technologies such as information technologies, microelectronics, artificial intelligence, advanced manufacturing and biotechnology, underpin the competitiveness of a range of industries. For industrial, financial and governmental leaders the definition and implementation of strategies that exploit opportunities created by advanced materials have been a challenge for almost a decade. The result of this view of technology as a strategic asset is that advanced materials, for one, are a priority and a focus program of a number of leading industrialized countries such as Japan, West Germany and the United States, amongst others.

The family of advanced materials include: advanced ceramics, advanced metals, polymers, and composites. Of these, advanced ceramics have received the most attention in the last decade. The timing of the present surge of interest in these materials is a result of a marriage between need and opportunity. The need for materials with superior mechanical, chemical, electrical, magnetic, optical and nuclear properties is greater than ever due to increased performance demands placed on the user sectors e.g., electronics, transportation, machinery and machine tools, communication and data processing, chemicals and petrochemicals, oil & gas, pulp & paper, medical and manufacturing industries. Technological breakthroughs, achieved in the last few years in the processing and microstructural control of these new ceramics to attain optimum performance properties, provide opportunities for fulfilling these needs. Also, the projected huge global market potential, estimated to be about US$ 20-30 billion by the year 2000, is catalyzing the businsess community to enter new fields of endeavour.

From a technological point of view, the development of advanced ceramics, as well as other advanced materials, has brought a revolutionary change in the field of engineering. Never before have engineers had an opportunity to design the materials they use, as well as the structures they build. In fact, with advanced ceramics and

composites, the very concept of materials and products merge together, joined by the new concept of integrated design. Such designs consolidate discrete parts and functions into a single, multifunctional structure (product), leading to highly efficient use of materials and low overall costs. Also, increasingly, the impetus for technological change is coming from engineers and designers at the user end, as science continues to improve industry's ability to customize materials for specific uses. Integrating and networking are the watchwords, as linkage among product designers, manufacturers, materials experts and others concerned with product performance grow stronger.

The changes in the materials world are of two types. The first is the shift in materials decision making to the user end i.e., the increasing influence of product engineers and designers over the type of materials that go into their product. Specifications are being dicatated more and more by unique performance requirements and less by the availability of standard materials. This opens the door for innovative materials processors to capture market niches with high value-added products.

The second type of change involves the response of governments and business to accepting advanced ceramics as a strategic technology, either by themselves or as part of the family of advanced materials. Strategic technologies, by definition, are enabling technologies, and are generic in nature. They are not peculiar to any given product line or industrial sector. Rather than being peculiar to any particular sector, they anchor the performance of many industrial sectors. They will be the keys to competitiveness in a range of industries in the future. To date governments in Japan, the United States, W.Germany, Sweden and the EEC have recognized the role of advanced ceramics in developing national strategies.

This study is a result of the recognition that one of the most important barriers limiting growth in the manufacture and use of advanced ceramics in Canada is the lack of specific information linking technology, products and markets. The majority of advanced ceramics manufacturers are small and, therefore, are limited in generating data on their own. The potential users, on the otherhand, are not familiar with the fast growing advanced ceramic technology and the performance/efficiency/productivity benefits and gains that could be achieved in their operations. The findings of this study are expected to assist government agencies in initiating policies/activities in support of Canadaian industry requirements.

The central issues of this study are: to identify and assess the technological and commercial status of advanced ceramics; to delineate market opportunities for Canadian manufacturers and users of advanced ceramics; and to recommend initiatives required to take advantage of these opportunities.

2. OBJECTIVES

The overall objectives of the study are:

i. To assess the impact of international developments in advanced ceramics on Canadian industry in terms of: technology, products, market potential and penetration.

ii. To acquire and analyze market data on advanced ceramics manufactured in Canada as well as imported into Canada in terms of specific user industry sectors.

iii. To identify manufacturers and users of advanced ceramics products in Canada,

iv. To recommend initiatives required to meet the needs of Canadian industry.

3. METHODOLOGY

The information assembled in this report was obtained from the sources listed below:

- Published scientific and technical literature, government and private industry reports, books, and manufacturers catalogues listed in Appendix 1.

- Information obtained by in-depth discussions with experts from universities, R & D establishments and industry listed in Appendix 2.

In the analysis and assesment of data, special emphasis has been given to commercial and industrial requirements/developments rather than to purely scientific and technological issues. The conclusions and recommendations reflect the needs of industry in terms of technology priorities and institutional support.

4. STATUS OF ADVANCED CERAMICS

4.1 Definition and Classification

"Ceramics" - from the Greek word "keramos" is a term which encompasses a wide variety of inorganic materials. The present-day definition is broader than the historic one: the art and science of making articles by the action of heat on earthy raw materials. The current generally accepted definition, adopted originally by the US National Academy of Sciences, is: an inorganic, non-metallic material processed or consolidated at high temperatures". In composition, they are a diverse group of inorganic materials comprisingg oxides, carbides, nitrides, borides and graphite. In Europe and many other countries the term "ceramics" and "glass" are distinguished from one another, at least by industry. In North America and Japan, however, the term "ceramics" includes glass.

Today, ceramics are divided into two groups, traditional and advanced. The family of traditional ceramics comprise of materials and products used by the general public (consumer market) and primary industries for generations. Typical examples are: pottery, bricks, dinnerware, sanitaryware, insulation (thermal and electric), glass (containers and sheet), and refractories.

Advanced ceramics go under several names. In North America, they are frequently called "high-performance" or "advanced ceramics", whereas in Japan they are called "fine ceramics", because usually they are prepared from very fine powders. In all cases, however, the term refers to a broad and diverse group of ceramic materials. Their distinguishing features, in general, are: superior properties leading to a substantially higher level of cost effective performance, much more stringent requirements on composition control and processing, and a market value based on unique performance delivered which justifies a much higher cost.

No formal definition which has international acceptance has yet been adopted to describe the term "advanced ceramics". In practice, however, the following definition applies: Advanced ceramics are improved/new materials with superior properties which make them technically superior compared to conventional ceramic materials; the term refers both to new materials made by conventional/new processing techniques, and to old materials made by new processing techniques, the criteria being superior properties".

Advanced ceramics are distinguished from traditional ceramics in that they are made from synthetic raw materials. Synthetic ceramic powders are required because of the need to control chemical compositions accurately as well as to achieve the required properties by controlling the microstructure during processing.

4.2 Properties of Advanced Ceramics

It is now generally recognized that the present and future uses of advanced ceramics are related to the diverse functional properties possessed by these materials. This recognition came about because of two reasons. Firstly, the realization that new materials with superior properties can be developed by the application of modern science and engineering concepts. Secondly, the participation of material scientists and engineers with diverse scientific and technological backgrounds e.g., physicists, chemists, metallurgists, ceramists and engineers who have approached the development with vigour and imagination.

In developing and using advanced ceramics, it is necessary to take into consideration the functional properties required to meet specific end use. The relationship between functions, properties and applications is given in Figure 1. Some of the unique properties of advanced ceramics which make them specially useful for various high performance applications are:

. High degree of hardness
. High melting point
. High temperature mechanical strength
. High wear/erosin/corrosion resistance
. Low density
. Low or high thermal conductivity
. High electrical resistivity
. Semiconducting properties
. Piezoelectric/pyroelectric properties
. Magnetic properties
. Optical properties

4.3 Classification

Although basic research on high performance ceramics was initiated in the U.K. as early as the 1950's and in the U.S. in the early 1970's, classification of advanced ceramics was not addressed until recently. A system of classification adopted by the Ministry of International Trade and Industry in Japan, shown in Figure 1, is now universally accepted.

Advanced ceramics are generally used as components because they perform many functions better than competing metals and polymers. Depending upon applications, they are classidied into two groups based on their functional properties. The two groups are:

- Advanced Structural Ceramics
- Advanced Functional Ceramics

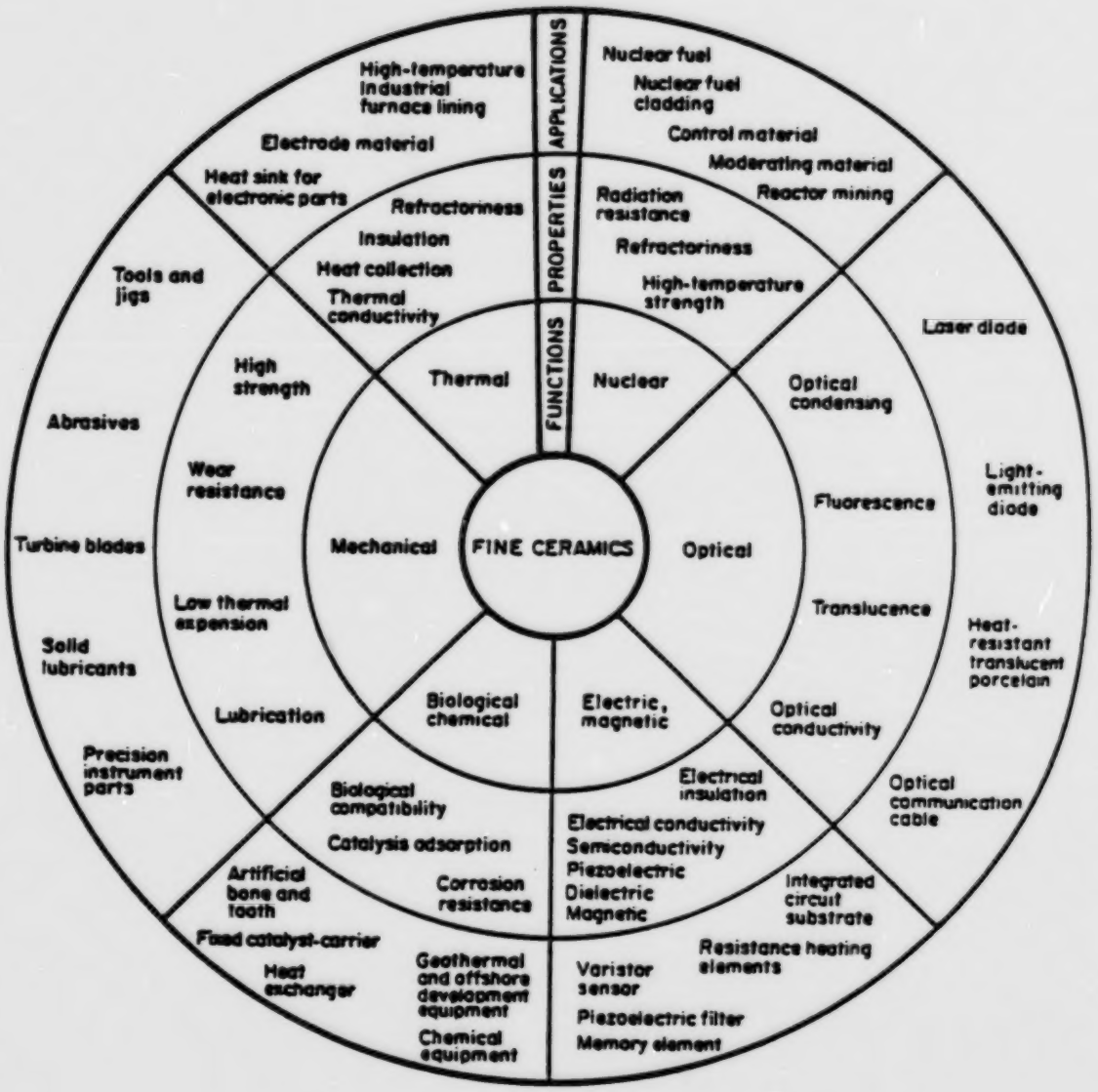


Figure 1. Relationships between Functions, Properties and Applications of Advanced Ceramics (after MITI)

4.3.1 Advanced Structural Ceramics

Advanced ceramic materials belonging to this group are characterized by good mechanical and/or thermal properties. In addition, they have to satisfy chemical property requirements e.g., corrosion resistance in the environments where they are used.

The three important mechanical property requirements are: high hardness and toughness, wear resistance, and high temperature strength. Typical materials and their applications are listed below:

Material	Property	Applications
Al_2O_3, SiC Si_3N_4, WC	Hardness & Toughness	Cutting tools Mechanical seals Die Inserts
Al_2O_3, ZrO_2 Si_3N_4, SiC	Wear Resistance	Rocket nozzles Bearings Pump components Engine components
SiC , Si_3N_4 Sialons	High Temperature Strength	Burner nozzles Engine components

The three important thermal property requirements are: a range of thermal expansion coefficients, a range of thermal conductivities, and stability at high temperatures. Depending upon applications, the materials must meet both mechanical and thermal property requirements. Some typical materials and applications are listed below:

Material	Property	Applications
$LiAl_2SiO_6$ $MgAl_4Si_5O_{18}$	Thermal Expansion	Regenerators Recuperators Ceramic-metal joints
Al_2O_3, AlN ZrO_2, SiC	Thermal Conductivity	Heat exchangers Thermal insulation Engine components
Al_2O_3, ZrO_2	Non-combustible	Fire safety

Extensive R&D programs are in place for the development and commercialization of the foregoing materials, their processing into components, and the testing and evaluation of the components for various applications.

From a technological and processing point of view, the structural ceramics that are being developed can be classified into three groups:

Oxide ceramics: Al_2O_3, ZrO_2, Silicates
Non-oxide ceramics: SiC, Si_3N_4, Sialons, AlN, BN, B_4C etc.
Composites: SiC-Si_3N_4, TiC-SiC, BN-SiC, BN-Si_3N_4 etc.

4.3.2 Advanced Functional Ceramics

The advanced functional ceramics category comprise materials whose electronic/electrical, magnetic, optical, chemical, biological and nuclear functional properties are taken advantage of in applications. From an application point of view, they are usually grouped as follows:

. Electronic/electrical properties
. Chemical and biological properties
. Nuclear ceramics

From a functional properties point of view, nine different types of electronic/electrical ceramics can be identified as shown in Figure 2. The relationship between type, property, composition and application is given in Table 1. These materials will be discussed in some detail in a subsequent chapter.

Ceramics are finding increased use for chemical and biological applications. The use of ceramics as catalysts in chemical processes is well established, however, new applications are being recognized. One of the important areas of development is "membrane" technology for separation of gases and liquids, which is expected to have significant technological and commercial impact in the coming decades.

Ceramic teeth have been used for several decades. However, with the availability of advanced ceramics with good chemical and mechanical properties, their use as roots for teeth and other implant purposes is receiving considerable interest. Hip joints made of inert alumina have been in use for some time. In Japan, implants related to artifical teeth are already being used and the market for this product alone is expected to be several hundred million dollars. Active work is in place to develop bioglass materials for various applications. Because of their inertness and stability, ceramic components are also finding increased use in medical equipment e.g., pumps and filters.

Nuclear ceramics have limited commercial significance.

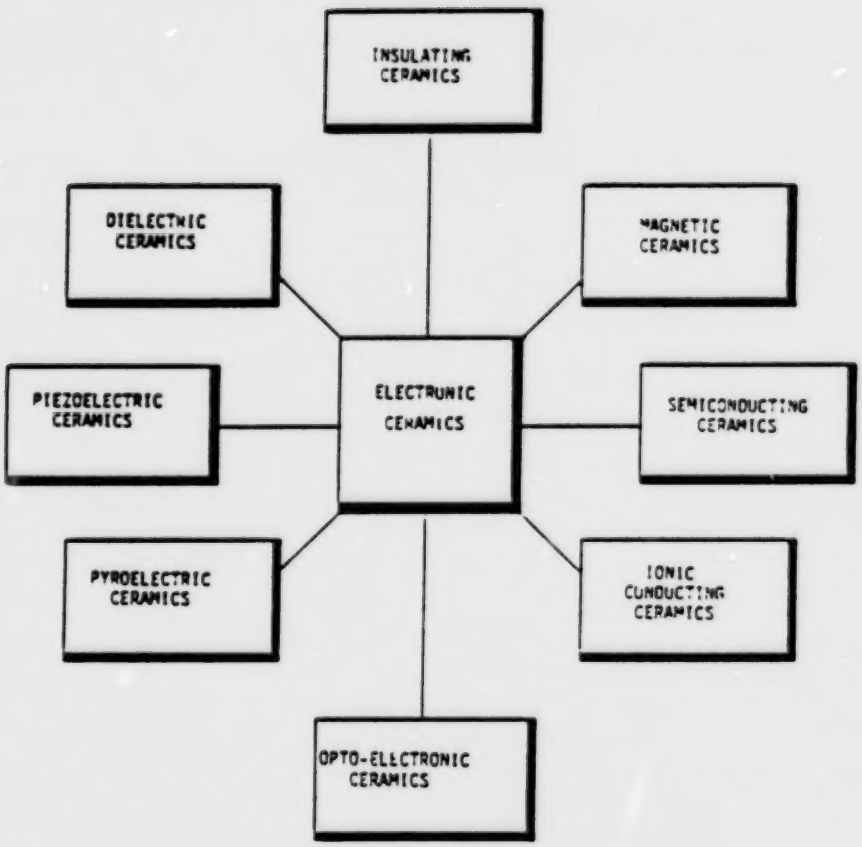


Figure 2. Different Types of Electronic Ceramics

TABLE 1

Applications of Electronic Ceramics

Type	Properties	Material	Applications
Insulating	Non-Conducting	Al_2O_3, MgO BeO	IC substrate, MLC packaging, Hybrid circuit substrate, Capacitor and Resistor substrate
Dielectric	Charge-Storage	$BaTiO_3$, $SrTiO_3$	Ceramic capicitors, Microwave filters, Trimmers
Piezo-electric	Interconversion of electric - mechanical energy	PZT	Vibrators, Filters, Oscillators, Spark Generators, Surface Acoustic Wave (SAW) Technology
Magnetic	Magnetic	$MnZnFe_2O_4$, $Ba_6Fe_{12}O_{19}$	Magnetic recording head, Temperature sensor, Permanent magnet, TV cores Speakers, Computer peripherals, Magnetic tapes
Opto-electronic	Optical-Electronic	Al_2O_3, PLZT, Y_2O_3	High voltage sodium lamp, Laser materials, Optical windows, Light Memory Element (LEM)
		$LiNbO_3$	Video display & storage, Light Shutter & Valve, Communication devices
Pyroelectric	Infrared Sensistivity	SbSi + glass SbSi + polymers CdMgTd	Fire & Smoke detectors, Vidicons IR detectors
Ionic Conductor	Ionic Mobility	beta-Al_2O_3	Sensors, Battery separator
Semi-Conductor	Electronic Mobility	$BaTiO_3$, SiC, ZnO, V_2O_5	NTC Thermistor: Temperature sensor & compensator PTC Thermistor: Heater element, Temp. controller CTR Thermistor: Heat sensor element Thick Film Thermistor: IR sensor Varistor: Noise elimination

4.4 Status of Advanced Structural Ceramics

4.4.1 General

Advanced structural ceramics with high-strength, high erosion, wear and corrosion resistance are being developed for a variety of applications. These materials are used as both monolithic components and as coatings depending upon the requirements of their intended applications. In this section, only monolithic ceramics are discussed. Coatings are discussed in a separate section.

The important candidate materials that are being developed for application in the monolithic component form can be grouped into three categories, namely, non-oxide ceramics, oxide ceramics and composites, as listed below:

Non-oxide Ceramics	Silicon carbide,	SiC
	Silicon nitride.	Si_3N_4
	Sialons,	$Si_{6-x}Al_xN_{8-x}O_x$
	Boron nitride,	BN
	Boron carbide,	B_4C
	Aluminum nitride,	AlN
	Others,	TiB_2 , TiC, TiN etc.
Oxide Ceramics	Pure oxide,	Al_2O_3
	Transformation-toughened,	ZrO_2 (PSZ, TTZ) Al_2O_3, $3Al_2O_3.2SiO_2$
	Low-expansion silicates,	$LiAlSi_2O_6$ $Mg_2Al_4Si_5O_{18}$
Composites	Ceramic matrix composites,	SiC-TiC, SiC-Si_3N_4 etc.,
	Metal matrix composites,	Al-Al_2O_3, Al-SiC, etc.,

First generation material compositions and process technologies for most of these materials have already been developed. Also, many of these materials have already found useful industrial and engineering applications. Nevertheless, a number of scientific, technological and cost barriers need to be overcome to realize the huge global market potential, projected to be about US$ 7-10 billion by the year 2000.

From a materials technology development point of view, three important barriers have been identified. They are:

- Reproducibility in manufacturing
- Reliability in service
- Manufacturing cost

Due to the inherent brittle nature of cermic materials even the smallest flaws, introduced during the material processing and component fabrication steps, will have serious deleterious effects on performance and reliability. Recently, an expert U.S.Committee, headed by Professor.H.K. Bowen of MIT concluded that: "The over-riding problem of high performance ceramics is that components with the desired properties and microstructure cannot be reliably and reproducibly manufactured". It is now generally recognized that the essential origin of the lack of reproducibility and rerliability of advanced ceramics resides in the extreme sensitivity of several important properties to relatively small-scale microstructural heterogeneities (such as pores, inclusions and cracks), coupled with the problems associated with the evolution of the desired microstructure during processing. There is general consensus in the scientific community that these problems are related to the nature and quality of the starting ceramic powders as well as limitations in the existing processing techniques. The cost problems arise not only because of the high cost of high quality ceramic powders and specialized manufacturing processes, but also becuase of poor yield in the manufacturing operations. Additional cost elements occur because of the finishing steps required to meet the rigid engineering dimensional tolerances and non-destructive testing to establish quality.

The foregoing problems are serious only in relation to the manufacture of advanced ceramic components for heat engine applications, which have to meet stringent tolerance and performance requirements. Until satisfactory solutions are developed, the use of monolithic advanced structural ceramics for engine applications is not expected to materialize in any significant way i.e., the projected market potential cannot be penetrated and captured.

The use of structural components for non-engine industrial applications, where reliability parameters and tolerance requirements are less demanding, is expected to grow rapidly for three reasons. Firstly, advanced ceramics manufacturers are under pressure to recover some of the huge R&D expenditures incurred to date. Secondly, the manufacturers are recognizing that the materials and materials technology available to date is adequate to meet the requirements of many non-engine industrial applications. As a consequence, there is increased effort to commercialize the existing technology to meet the needs of other sectors of the economy such as: mining and mineral processing; petrochemical, petroleum and chemical industry; machinery

and machine tool industry; and pulp & paper industry. Thirdly, product and design engineers, having recognized the advantages of using advanced ceramic components, are using design considerations to overcome some of the material-imposed limitations to gain efficiency/ performace advantages.

4.4.2 Status of Materials Technology and Applications

Serious research efforts to develop advanced ceramics for structural applications originated in the United States in the early 1970's, followed by West Germany and Sweden. Although Japan did not initiate R&D until 1978, it is now considered the world leader in the commercialization of these materials. However, the United States is still considered to be the world leader in the science and technology of advanced ceramic materials.

A comparison of the international efforts in the development of advanced structural ceramics is given in Figure 3 to illustrate the competition faced by Canada. The bulk of these international efforts have been in the development of non-oxide materials such as silicon carbide, silicon nitride, sialons and toughened oxides, particularly zirconia and alumina ceramics. The status of these materials and applications will be reviewed briefly.

4.4.2.1 Non-oxide Ceramics

The three materials in this category which have received significant attention over the last 15 years are:

- Silicon carbide, SiC
- Silicon nitride, Si_3N_4
- Sialons, $Si_{6-x}\ Al_x\ N_{8-x}\ O_x$

The importance of these materials arises from the fact that they have very high melting points and hardness, and can be made into monolithic ceramic components with very good mechanical properties, particularly high-temperature strength required for heat engine applications. R&D efforts are still continuing. Whereas there are still many uncertainties regarding the commercial success of these materials for engine applications, there are no such reservations regarding their utilization for non-engine industrial applications(*).

(*) "The Future for Advanced Ceramics - The Numbers Game or Reality". E.Sundberg, Norton Company. Paper presented at the CUICAC Workshop, Toronto, May 25-26, 1987.

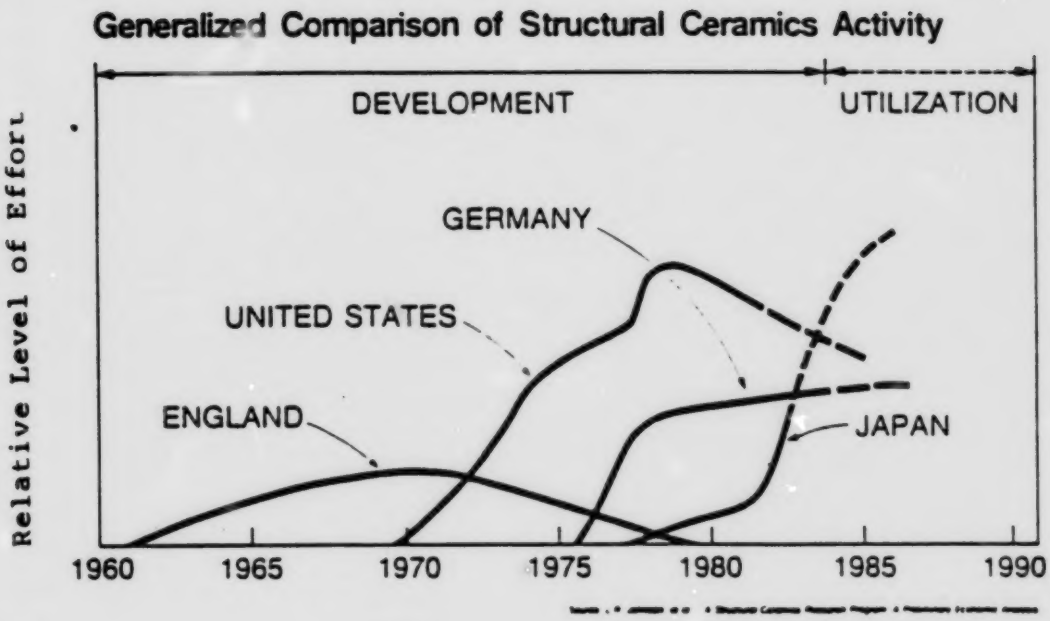


Figure 3. Relative Level of International Effort in the Development of Advanced Structural Ceramics for Engines

Silicon Carbide

Silicon carbide was first developed as an engineering material for abrasive applications almost 90 years ago because of its high hardness. Subsequently, because of its high melting point and resistance to erosion and corrosion, it found applications as a refractory in metallurgical operations. Since it could not be sintered into a high strength ceramic in air, binders such as clays and carbon pitch were used in the manufacture of silicon carbide refractory bricks.

Considerable amount of R&D was done in the time frame 1950-1960 to develop alternative processing for the manufacturing high-density and high-strength silicon carbide ceramics. Hot pressing techniques were pioneered in the USA to meet the requirements of defence applications such as armour plates, nose cones for misciles etc. Recrystallization techniques were developed by Norton. However, none of these processes really met the market needs in terms of price and quality. The hot-pressing technique was too expensive and only simple shapes (plates and discs) could be made. The Norton recrystallization process did not give very high strength material.

The development of silicon carbide as an engineering material for nuclear cladding applications was pioneered by the UK Atomic Energy Authority and a patent was obtained in 1970. Since SiC powders (available at that time) could not be sintered into dense ceramics using conventional oxide-ceramic processing techniques, an indirect method called the "REFEL" technique was developed. In this process, fine α-SiC and graphite powders are mixed with an appropriate plasticizer, formed into shapes by conventional ceramic shaping techniques, and heat treated with molten silicon to convert the graphite powder into silicon carbide. The Refel silicon carbide ceramics have been used for many engineering applications since the early 1970's; and many similar modified methods have been developed by several other manufacturers. Although the Refel silicon carbide ceramic has many useful engineering properties, it suffers from two important limitations. Firstly, because of the presence of free silicon metal (about 8%), it cannot be used at very high temperatures, particularly at temperatures required for operating heat engines. Secondly, the process is expensive and cannort be adopted for mass production. A schematic of the process is shown in Figure 4.

Over the years, four processes have been developed for the manufacture of silicon carbide ceramic components and parts. They are:

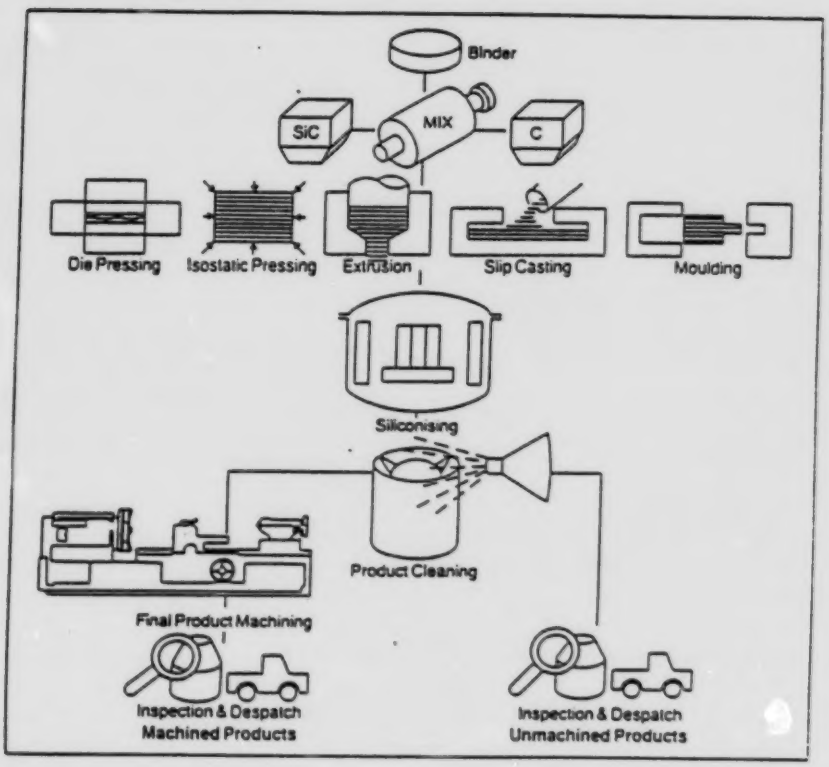


Figure 4. Schematic of the Refel Process for the manufacture of Silicon Carbide Cersmics by the Reaction Bonding Technique

Process Type	Product Type
. Hot Pressing Techniques (HP)	HPSiC
. Reaction Bonding Techniques(Refel)	SiSiC
. Hot Isostatic Pressing Technique(HIP)	HIPSiC
. Pressureless Sintering Technique	SSiC

Hot pressing technique is rarely used for commercial production. However, it is used as a research tool.

The Refel process, or modifications thereof, is being used by a number of silicon carbide manufacturers. The important manufacturers are listed below:

- British Nuclear Fuels Ltd. UK (*)
- Electroschmeltze Kempten, W.Germany
- SIGRI, W.Germany
- Feldmuhle, W.Germany
- Hoechst(Rosenthal), W.Germany
- Asahi Glass, Japan
- Norton Co, USA
- Sohio Engineered Materials Co, USA
- Coors, USA

The Hot Isostatic Pressing (HIP) technique is a modification of hot pressing technique in that the pressure is applied through an inert gas (e.g., argon) so that complex shapes can be produced. Because the method is capable of producing high-quality near-net-shape products it is being adopted for commercial production. Special technologies and equipment have been developed by ASEA in Sweden which has been licenced to a number of manufacturers in the USA (e.g., Norton). In Japan, Kobe Steel is active in the development of equipment and process technology.

The most important development in the manufacture of silicon carbide ceramics for engineering applications, from the commercial point of view, is the development of pressureless sintering technology made possible by the discovery of Prochazka of the General Electric Company in 1973. He showed that by the addition of sevel tenths of one per cent of boron and carbon to submicron β- SiC powders, one can obtain near theoretical density components.

(*) During a visit to British Nuclear Fuels Ltd., it was found that the company is looking at a US$ 100 million market in North America, mainly for applications as mechanical seals. It was expected to compete against high-price-end alumina and low-price-end tungsten carbide components.

Sohio Engineered Products Co (formerly Carborundum Co) has more recently developed pressureless sintering techniques for α-SiC powders and the product is sold under the trade name "Hexoloy SA". Since conventional ceramic fabrication techniques such as die pressing, isostatic pressing, injection molding, or slip casting can be used, complicated shapes can be produced economically. The process is patented throughout the world and has been licenced by several manufacturers, particularly in Japan.

To date, the bulk of the silicon carbide advanced ceramic components are made from α-SiC powders. However, it is now recognized that better strength properties and performance can be achieved with β-SiC powders. Hence, the development and commercialization of these powders is becoming very important.

Both silicon carbide and silicon nitride are competing with one another for structural applications. Since the projected future markets are substantial, the competition is keen and intense. R&D efforts are in place to develop suitable material compositions and process technologies. Although at present silicon nitride has an advantage in terms of better strength-toughness properties, both materials suffer from high cost. The consensus is that whichever material is cost-effective will win the race.

Bulk of the evidence to date indicates that the demand for advanced structural ceramics will increase in the coming decades. Silicon carbide ceramics have been in the market place for almost two decades and have already achieved a degree of acceptance. It is estimated that the tonnage of the products is in the range 7,000-10,000 per year.

Almost all companies developing silicon carbide components for heat engine applications are also marketing/developing parts and components for many other applications. Typical present and projected applications are given in Table 2. A more detailed description of products and applications manufactured by important producers is given in Appendix 3.

Silicon Nitride (Si_3N_4)

Silicon nitride, Si_3N_4, known for over 70 years, attracted interest as a ceramic material some 30 years ago because of its high melting point, refractoriness, high-temperature strength and relatively low thermal expansion coefficient. Being a covalent material, it could not be sintered to high density using conventional ceramic technology. Hence, hot pressing techniques were developed as early as the 1960's and the excellent high-temperature mechanical properties, resistance to oxidation, and good thermal shock properties were recognized. This recognition resulted in interest in this material for developing new

TABLE 2

Typical Present and Projected Applications for Silicon Carbide Components

Industries	Environment	Application	Primary Benefits
Oil and Gas	High Temperature, Abrasive, High Fluid Pressures	Nozzles, Bearings, Seal Faces, Valve Seats, Choke Inserts	Abrasion and Wear Resistance
Chemical Processing	Strong Acids (Conc. HNO_3; H_2SO_4; HCl; HF) and Strong Bases (NaOH)	Seal Faces, Bearings, Pump Sleeves, Pump Components, Heat Exchanger	Wear & Corrosion Resistance, Impermeability
	High Temperature Oxidation	Gasifier Tubes, Thermocouple Tubes	Corrosion Resistance at High Temperatures
Automotive & Truck, Aircraft, Aerospace	Engine Combustion	Combustion Components, Turbocharger Rotors, Gas Turbine Vanes, Blades, Rocket Nozzles	Low Friction and High Strength, Low Inertial Loads, Thermal Shock Resistance
Automotive & Truck	Engine Oils	Valve Train Components	Low Friction, Wear Resistance
Sand Blasting	High Velocity Abrasive	Nozzles	Abrasion Resistance
Paper	Pulp-Black Liquor (50% NaOH)	Seal Faces, Sleeves, Bearings	Corrosion Resistance
	Pulp/Paper Slurry	Suction Box Covers, Foils, Forming Boards	Abrasion Resistance, Low Friction
Heat Treating, Furnacing Steel	High Temperature Air	Thermocouple Tubes, Radiant Tubes, Recuperators, Burner Components	Temperature and Corrosion Resistance, Impermeability
Mining & Mineral Processing	Abrasive	Linings, Pump Components	Abrasion Resistance
Nuclear	Boronated High Temperature Water	Seal Faces, Bushings	Radiation Resistance
All	In Process Forming	Wire Dies, Can Dies, Textile Guides, Molds	Abrasion, Wear and Corrosion Resistance

energy-efficient gas turbine engines in the 1970's. The early support came from the US government programs, followed by W.German and Swedish national programs. Japan initiated its national program in 1978 and now is the world leader in its commercial manufacture.

As in the case of silicon carbide ceramics, different routes have been developed for the manufacture of silicon nitride components. They can be summarized as follows:

Process Type	Product Type
. Hot Pressing Techniques	HPSN
. Reaction Bonding Techniques	RBSN
. Hot Isostatic Pressing Techniques	HIPSN
. Pressureless Sintering Techniques	SSN

Hot pressing techniques are used only for research and development. All the other techniques have found commercial acceptance to varying degrees. Reaction bonded silicon nitride components (RBSN) are made from a process similar to the Refel process used for silicon carbide. The starting powder is high purity, high surface area metallic silicon powder. The components are made to the desired shape by any of the conventional ceramic forming techniques and sintered in a nitrogen atmosphere using the required time-temperature-pressure conditions. The addition of well dispersed iron oxide in the silicon powder, and hydrogen-in-nitrogen atmosphere are used as standard techniques. The technology is well developed and world-wide commercial applications are estimated as about 10-20 tons per year.

Sintered reaction-bonded silicon nitride ceramic (SRBSN) is a relatively new technique used to obtain near-net shape and high strength products. In this process, the initial component preform is reaction bonded with the addition of suitable sintering aid, and further subjected to pressureless sintering to form a high density component.

In pure silicon nitride, the volume diffusivity is not large enough to offset the densification retardation effects caused by surface diffusion and volatilization phenomena. Hence, sintering aids are used to promote liquid-enhanced sintering at lower temperatures. The development of commercially useful silicon nitride ceramics using this technique is one of the most significant developments in this field.

Although dense silicon nitride can be obtained by the use of sintering aids, this process has a limitation. The properties of the ceramics, particularly at high temperatures, are controlled by the nature and amount of additives. As a result, there is not a single silicon nitride material, but a whole class of materials with a variety

of properties. Magnesium oxide, MgO, was used in the beginning as the sintering aid, however, now the preferred material is yttrium oxide, either alone or with aluminum oxide.

"Gas pressure" sintering is a modified, mild form of hot isostatic pressing, and has been developed with particular success for compositions based on the systems Be-Si-N-O and Al-Si-Y-N-O. Sintering to the closed porosity stage is carried out under low nitrogen over-pressure (0.1-2 Mpa), followed by increased pressure to 2-7 MPa to achieve rapid and full densification.

Sintering methods have one main disadvantage i.e., high shrinkage of about 15 per cent which makes it difficult to attain the desired net shape. However, technology has been perfected in Japan for the commercial manufacture of a number of engine components such as turbocharger rotors and precombustion chambers.

Commercial production is confined to just Japan, USA, and UK. There has been considerable growth in consumption, however, this has occured mainly in Japan. Production in Japan is estimated to be several hundred tons per year. In England, it is estimated to be about 20 tons per year. In the USA, GTE Sylvania and Greenleef are producing cutting tools. Other companies that are commercializing this material are Norton-TRW, Ford-Ceradyne, Eaton-GTE and Garrett. Tonnage information is not available.

Typical present and projected applications for silicon nitride components are given in Table 3. A more detailed description of applications and products manufactured by important producers is given in Appendix 3.

Sialon Ceramics ($Si_{6-x}\ Al_x\ N_{8-x}\ O_x$)

Sialon ceramics are a by-product of R&D on silicon nitride ceramics. Because high-density high-strength silicon nitride ceramics could not be made by pressureless sintering techniques, alternative technologies were developed. The Sialon family of ceramics are a result of the recognition, in the early 1970's, that aluminum and oxygen can substitute for silicon and nitrogen in the structure of silicon nitride which could lead to: (i) strong pressureless sintered materials; (ii) more chemically stable materials; and (iii) materials with better high temperature capabilities.

The original development was carried out at the University of Newcastle-upon-Tyne, UK, sponsored by the Lucas Company. However, the development of the technology took place in the laboratories of Lucas. Commercialization is being done by Lucas Cookson Syalon Ltd., a joint venture between Lucas and Cookson Group. The trade name for the products is "Syalon". Work is in progress both in Japan and in France

TABLE 3

Typical Present and Projected Applications for Silicon Nitride (Si_3N_4) Ceramics

Type	Applications
Reaction Bonded (RBSN)	Welding nozzles and insulators. Has been used since the 1970's.
	Non-ferrous foundries & diecasting. Is currently used in aluminum, lead, zinc, and their alloy foundry.
	Precision jigs and fixtures. Used in automatic welding and brazing operations.
	Heat-treatment processes.
Hot-pressed (HPSN)	Metal cutting. Cutting tools are used, particularly by automobile manufacturers.
	Tube drawing. Ideal material for plugs and dies in stainless steel tube manufacture.
	Seal faces. Applications in the pumping of corrosive and erosive liquids.
	Ball and roller bearings. Present use is small but expected to grow.
Sintered (SSN)	Engine components. Turbochargers, precombustion chambers, rocker-arm parts are already in commercial production. Many other components for gas turbine engine applications are under development.

for the development of different types of sialons, particularly using inexpensive raw materials such as clays.

Sialons are manufactured from high-purity ceramic powders comprising silicon nitride, silica, aluminum oxide and aluminum nitride. The sialon ceramics can be fabricated using conventional ceramic processing technologies. Hence, they have some advantages over silicon nitride. However, because of the need to use expensive starting powders, manufactured cost might not be much different.

Lucas Cookson Syalon Ltd., has licenced the technology to a number of manufacturers such as Sandvik (Sweden), Sohio Engineered Materials Co., (USA) and Asahi in Japan. Syalon cutting tools have already received market acceptance and are used extensively.

Typical industrial applications are given in Table 4.

4.4.2.2 Oxide Ceramics

The two important group of materials in this category are:

- Transformation toughened zirconia (TTZ), and alumina (TTA).

- Low expansion ceramics ($LiAlSi_2O_6$ and $Mg_2Al_4Si_5O_{18}$).

Transformation Toughened Zirconia Ceramics (ZrO_2)

Although zirconia based ceramics have been used for several decades as refractories, advanced zirconia ceramics with very high-strength and toughness properties are only of recent origin, and are less than a decade old. This development is usually attributed to Garvie and co-workers in Australia, who discovered that the strength and toughness properties of zirconia ceramics could be increased substantially by taking advantage of the tetragonal-monoclinic phase transformation of these materials.

When cubic zirconia, structure stabilized by using an oxide such as calcium oxide (CaO), magnesium oxide (MgO), or yttrium oxide (Y_2O_3) is cooled under carefully controlled time-temperature conditions, tetragonal zirconia phase can be precipitated out in the cubic matrix and can be retained in a metastable condition at room temperature. This arises out of the fact that the tetragonal-monoclinic phase transformation, which is accompanied by a 3-5 volume per cent expansion, is prevented by the cubic matrix enabling the tetragonal phase to be cooled to room temperature in a metastable condition. Increased toughness is achieved in this type of ceramic by the fact that a fracture interacts with the metastable tetragonal zirconia particle and the fracture energy is absorbed in the "martensitic"

TABLE 4

Typical Present and Projected Uses for Sialons

Applications	Components
1. Metal cutting	Cutting tools (indexable lathe inserts for high-speed cutting.
2. Welding	Gas shrouds and location devices. Small diameter gas shrouds are used in automatic welding operations in the aerospace industry.
3. Extrusing dies	Inverse, forward, single-shot impact extrusion and the Conform process using brass, copper, aluminum, bronze, titanium and steel-working materials.
4. Seals and Bearings	Wide ramge of seal and bearing applications. Roller, ball and trunion bearings for use in hot and erosive environment.
5. Mining	Sialon cutting tools have been used for cutting soft quatrzite rocks.
6. Armour plating	The ballistic impact resistance of sialon sialon ceramics is better than alumina and boron carbide.
7. Molten metal handling	Various uses are being developed.
8. Wear parts	The ability of sialon ceramics to operate in contact with metallic components with or without lubrication, and its ability to withstand high temperature enables a wide range of applications such as tube drawing dies, tube drawing mandrel plugs and roller guide plates.
9. Refractories	Sialon powder is included into other refractories to improve hot face performance and resistance to molten metal attack.

transformation into monoclinic zirconia, thus preventing the crack propogation through the ceramic. These materials are now designated as "transformation toughened" zirconia. The exact mechanisms i.e., the micromechanics of the toughening process still remains the subject of active research. However, two types of toughness producing mechanisms have been identified. In the first case, the martensitic transformation of tetragonal zirconia particles near the advancing crack tip is directly involved in the energy absorption process i.e., stress induced transformation. In the second case, nucleation and extension of matrix microcracks caused by the tranzformation of particles on cooling prior to specimen loading are responsible for increased energy absorption during crack propogation (microcrack nucleation and extension). Also, a combined effect of both the mechanisms seems possible i.e., first a stress-induced transformation and then microcrack nucleation.

It is now generally recognized that the foregoing transformation-toughening phenomena is not restricted to zirconia systems; and that they can be used for other ceramic systems as well. For example, small additions of zirconia can be used to increase the toughness of alumina ceramics (Al_2O_3), silicon nitride ceramics (Si_3N_4), and silicon carbide ceramics (SiC). This phenomena can also be used to generate compressive stresses on the surface of ceramics, thereby strengthening them. Also, fine grained tetragonal zirconia ceramics have been developed which have extremely high toughness values.

Selection of the proper "structure stabilizing oxide" and heat-treatment schedules to obtain the desired microstructure are the most important issues governing the processing of high strength zirconia ceramics. Both magnesium oxide (MgO), and yttrium oxide (Y_2O_3) are being used, however, the latter is preferred because it lowers the tetragonal-monoclinic transformation temperature permitting retention of larger particles at room temperatures.

The first commercialization of toughened zirconia was made by Nilsen Sintered Products Pty.Ltd., a subsidiary of Oliver J.Nilsen Ltd., of Melbourne, Australia. The Nilsen patents are covered worldwide. Recently, a new joint venture called Nilcra Ceramics Pty.Ltd., has been formed to exploit world markets.

In Japan a number of companies are active in the development of toughened zirconia ceramics using yttrium oxide as the stabilizing agent. The important manufacturers are: Kyocera and NGK. Both these companies are active in the development of components for engines as well as for industrial applications.

In the USA, the principal manufacturers are: Corning Glass, Cerac Inc, Ceradyne, Coors, Hi-Tech Ceramic Inc, and Lambertville Ceramics Mfg.CO. Typical industrial applications are given in Table 5.

TABLE 5

Industrial Applications for Zirconia Ceramics

Structural Applications

1. Components for gas turbine and automotive engine applications such as: cylinder liners, piston caps, valve guides, valve seats, tappet discs, thermal barrier coatings for diesel engines as well as gas turbine engines

2. Dies: Extrusion dies for hot extrusion of brass, copper wire, and low carbon steel seamless pipe, powder metallurgy dies for iron based components

3. Bioceramic applications: prosthetic sevices such as femoral ball and hip sockets

4. Industrial applications: abrasion resistance applications; cyclone discharge chutes; gem laps; speciality bearings.

Electrical Applications

5. Zirconia based oxygen sensors for automotive engine control applications; and industrial applications e.g., flue gas analysis, oxygen monitors for heat treatment furnaces, and hot diffusion and current limiting devices.

Transformation Toughened Alumina Ceramics (Al_2O_3)

Because of its high melting point (2025 ^{o}C), hardness, and chemical stability, alumina and alumina based ceramics have been used by industry for several decades. The early uses were as refractories and refractory products such as thermocouple tubes, crucibles etc., and as abrasives and abrasive products. However, starting in the early 1940's, two new important uses emerged: (i) cutting tools and (ii) substrates for electronics. Alumina based cutting tools have been in use since the middle 1940's, however, are now facing competition from silicon nitride and sialon based materials. The use of alumina substrates for electronics has grown rapidly and now forms one of the most important commercial application.

Amongst oxide ceramics, alumina ceramics hold a dominant position in the martket place accounting for more than 50%, the most important market being the electronics industry. The largest world suppliers of alumina ceramics for the electronics industry are Japanese manufacturers, both in Japan and in the USA, e.g., Kyocera and NGK.

Interest in alumina ceramics for mechanical applications has been revived because of the recognition that its mechanical properties, particularly toughness, can be significantly improved by using the science of "transformation toughening". Transformation toughening was previously thought to be a phenomenon inherent only in zirconia ceramics. However, it is now recognized that it is applicable to alumina ceramics as well as a number of other materials such as silicon nitride, silicon carbide, mullite ($3Al_2O_3 .2SiO_2$), and spinel ($MgO.Al_2O_3$).

The most successful commercial example in which transformation toughening techniques have been applied amongst the foregoing materials are those based on alumina. This has been achieved by the incorporation of about 15-18 volume per cent zirconia in alumina. The development of toughness requires stringent control of composition and microstructure. Toughened alumina ceramics are now used as cutting tools and as abrasives. Very recently, Champion Spark Pluf Company., in the United States has announced the development of zirconia-toughened alumina (ZTA) with the trade name "Ceraform". The company has developed materials and process technologies for the manufacture of components for automotive engines and other applications (Table 6). Considerable R&D effort is being expended on the development of toughened ceramics based not only alumina but also on other materials. It is anticipated that many new materials will be forthcoming in the coming decades.

TABLE 6

Prototype Applications for Zirconia Toughened Alumina

Application	Component	Advantage
Auto/Truck Gas and Diesel Engines	Rocker Arm Roller Valve Lifter Roller	Reduced friction and wear vs metal or ceramic insert flat followers. Simplicity over metal roller/needle bearing assembly.
	Valve guide Valve seat	Improved wear and corrosion resistance vs metal components.
	Valve	Help maintain designed engine performance over a longer interval than metal components.
	Wrist pin	Inertia weight reduction.
		Potential of operating with reduced lubrication.
Truck Diesel Engine	Crown on Aluminum Piston	Inertia weight reduction over mechanical strength of ceramic/aluminum composite over aluminum alone.
Ballistic Armor	Ceramic Tile	Improved strength to weight ratio over conventional alumina bodies.
		Improved ballistic threat level capability.
Production Tooling e.g. Inserts hot metal pins in TV tube face plates	Pinchucks	High compressive strength. High thermal shock resistance. in 400 to 2500°F range for thousands of 20 sec. cycles,(fast, heat up, fast cool down).
		High oxidation resistance.

Source: Champion Spark Plug Co.

Low-expansion Ceramics ($LiAlSi_2O_6$ and $Mg_2Al_4Si_5O_{18}$)

Low expansion ceramics are required for many high performance applications where resistance to thermal shock under cyclic operating conditions is a requirement. Materials based on lithium alumino - silicates (spodumene) and magnesium alumino-silicates (cordierite) have been used for this purpose for many years.

These low expansion ceramics are made by both conventional ceramic processing techniques and the glassceramic techniques. They are commercially used in many industrial and automotive applications e.g., cordierite based catalyst supports have been used in automotive exhaust systems for almost a decade.

These materials are also candidate materials for the construction of high temperature regenerators required in the commercialization of adiabatic diesel and gas turbine engines. Considerable amount of R&D work is in place to improve the materials technology to obtain high - strength materials.

4.4.2.3 Composites

Most ceramics are composites in the sense that they contain more than one discrete crystalline and/or glassy phases. In many cases, however, this structure is not seen as giving specific advantages in terms of properties, although there may well have been advantages concerning ease of fabrication.

The term "composite" is usually reserved for expressly fabricated materials incorporating two or more phases, where there is an intention to improve the properties over and above those expected from conventional materials. "Composite" material may be defined as a synergistic assembly of two or more materials where the properties of the composite often exceed those of the individual components.

To date, the "composite" concept has been generally used to achieve high mechanical strength/weight ratios, both for room temperature and high temperature applications. However, the concept is being extended to other types of ceramics e.g., piezoelectric ceramics for transducer and other applications. The present discussion is limited to composites with enhanced mechanical properties i.e., for structural applications.

The main mechanical properties of a composite are governed by the properties of the reinforcements. These reinforcements may be used in the form of fibres, whiskers, flakes or irregular particles. Reinforcements are dispersed in another material known as "matrix", whose main role is to transfer stress between individual reinforcement particles, protect them and form the shape.

Composites are often classified by the type of matrix. Several types of composites are recognized: thus there are polymer, carbon or graphite, ceramic and metal composites.

Four types of advanced structural composites are being developed. They are:

- Organic matrix composites with carbon, Kevlar, boron and S glass (glass with higher strength than E glass) fibres;
- Carbon matrix with carbon fibres;
- Ceramic matrix composites (CMC's);
- Metal matrix composites (MMC's).

Only the last two categories will be discussed in this report because both of them use advanced ceramics either as matrix and/or as reinforcement materials.

Ceramic Matrix Composites

Ceramic matrix composites are an active and expanding field of development. Most of the research and development has occured in recent years. Major advances are expected to be made in the next few years in high temperature structural materials for use up to 2200 ^{o}C, and in structural materials for use in reciprocating engines at lower temperatures. Other room temperature applications are expected to evolve as processing costs come down.

Although monolithic advanced ceramics have been developed for many important applications requiring high mechanical strength, abrasion and corrosion resistance, their commercial use has been restricted because of one major limitation, namely, brittleness, that renders service life unpredictable. The impetus for the development of ceramic matrix composites stems largely from the need to improve the fracture toughness and strength of monolithic ceramics while retaining all their intrinsic merits. Theoretical advances are being made to address the complicated issue of interrelating the size of the dispersed particles or fibres, their spacing in a ceramic matrix, the property differnces between matrix and reinforcement, and the typical flaw-size that affects strength. Systematic research work is directed toward demonstrating these concepts with materials systems that show high promise for specific applications. In these efforts, advantages are being taken of the technologies developed for reinforced metal and resin matrix materials.

Matrix Materials

Three types of ceramic matrix composites can be identified: non-oxide matrix materials; oxide matrix materials; and glass matrix materials. Non-oxide matrix composites are made up of either carbides, borides, or nitrides as matrix material. Bulk of the present day developments are based on silicon carbide, silicon nitride, titanium carbide and boron nitride. Amongst the oxide matrix composites, alumina and zirconia are the principle matrix materials. Glass matrix materials, specifically glassceramic matrix composites are also receiving considerable attention.

Reinforcements

From a compositional point of view, the choice of reinforcement material is as diverse as the ceramic matrix itself. However, all these reinforcing materials are basically used in two distinct physical forms, namely, fibres and/or particulates. Common fibre materials include graphite; metals such as boron, tungsten, niobium and stainless steel; glass and ceramics such as fused silica, borosilicates, alumina and silicon carbide. Most of these materials are atleast as strong as the ceramic matrix and are normally incorporated into the matrix to improve mechanical strength and fracture toughness through a load transfer mechanism and by inhibiting crack propogation. Typical properties for some fibres are listed in Table 7. Particulate materials are usually glass and ceramics but, in certain cases, metals are also used.

Ceramic Matrix Composites

A typical ceramic matrix composite is made up of very fine fibres or particulates embedded in an otherwise monolithic ceramic body. The fibre or particulate reinforcement may be arranged randomly or in a partially or completely oriented manner, depending upon design requirements. All these systems show substantially improved strength, fracture toughness and thermal shock resistance as compared with their monolithic ceramic counterparts. A brief comparison of the properties is given in Table 8. In principle, CMC components can be produced in two stages. Firstly, by the incorporation of the reinforcement in the unconsolidated matrix material, followed by consolidation of the reinforced matrix, usually involving heat-treatment and pressurization. Secondly, these two stages can be combined into one process. Typically, consolidation of CMC's is done in the temperature range 1000-2000° C. Preforming the composite to the desired shape, however, is accomplished at room temperature. High temperature densification is carried out either by hot pressing, HIPing, or superplastic forging.

TABLE 7

Typical Properties of Common
Fibre Reinforcement Material for CMC's
(From Fabrication of Composites, North-Holland, 1983)

Fibres	Young's modulus (GPa)	Tensile strength (MPa)	Thermal expansion coeff. α (10^{-6} °C^{-1})	Density ϱ (g × cm^{-1})	Fibre diameter d (μm)
High modulus carbon[a]	360	2400	radial 8 axial 0	1.8	8
Silicon carbide yarn from organo-metallic polymer[b]	220	2060	4.8	2.7	10
Silicon carbide deposited on carbon filament[b]	415	3450	4.8	3.2	140
α-alumina[c]	385	>1400	8.5	3.9	20
Alumina–borosilicate[d]	152	1550		2.5	11
Boron	420	3000	8.2	3.4	100
Tungsten	340–410	2900–3800	4.8	19.3	
Niobium	83–124	500–1030	8.1	8.6	
Stainless steel	150–210	2050–2550		7.7–8.0	

TABLE 8

A Comparison of Fracture Toughness and Critical Flaw Size of Monolithic and Composite Ceramic Materials

Material	Fracture toughness (MPa· $m^{1/2}$)	Critical flaw size (micrometers)
Conventional microstructure:		
Al_2O_3	3.5-4.0	25-33
Sintered SiC	3.0-3.5	18-25
Fibrous or interlocked microstructure:		
Hot pressed Si_3N_4	4.0-6.0	33-74
Sintered Si_3N_4	4.0-6.0	33-74
SiAlON	4.0-6.0	33-74
Particulate dispersions:		
Al_2O_3-TiC	4.2-4.5	36-41
SiC-TiB_2		
Si_3N_4-TiC	4.5	41
Transformation toughening:		
ZrO_2-MgO	9-12	165-294
ZrO_2-Y_2O_3	6-9	74-165
Al_2O_3-ZrO_2	6.5-15	86-459
Whisker dispersions:		
Al_2O_3-SiC	8-10	131-204
Fiber reinforcement:[b]		
SiC in borosilicate glass	15-25	
SiC in LAS	15-25	
SiC in CVD SiC	8-15	
Aluminum[c]	33-44	
Steel[c]	44-66	

[a]Assumes a stress of 700 MPa (~100,000 psi).
[b]The strength of these composites is independent of preexisting flaw size.
[c]The toughness of some alloys can be much higher.

SOURCES: David W. Richerson, "Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report for OTA, December 1985, and Elaine P. Rothman, "Ultimate Properties of Ceramics and Ceramic Matrix Composites," contractor report for OTA, December 1985.

Silicon nitride particle reinforced silicon carbide composites, developed by Norton Co., have been in use since the early 1970's as high temperature die material. New composite materials with silicon nitride fibres as reinforcing phase are under development. Other carbide based composites include titanium carbide particle reinforced silicon carbide and beryllia/silicon carbide composites. Titanium diboride matrix composites have been developed for electrode applications for use in aluminum metal manufacture. Considerable amount of work on nitride matrix composites is in progress; silicon carbide whiskers and fibres are used in silicon nitride matrix to improve fracture toughness and strength. Boron nitride additions have been made to silicon nitride to improve thermal shock and electrical behaviour.

Silicon carbide whisker reinforced alumina cutting tools are now commercially made by Greenleaf. Titanium carbide reinforced silicon carbide components are now being commercially produced by Sohio Engineered Materials Co., for use in oil and gas exploration drilling.

A large number of potential applications exist for CMCs. In the military sector, they include radomes, re-entry space vehicle antenna windows and nosetips, armour, engine components, heat exchangers, bearings and nozzles. Other prominent areas of intended uses of CMCs are in the energy related technologies, such as semi-structural components for nuclear fission and fusion reactors, large scale solar energy conversion systems, coal liquification and gasification, high-energy-density batteries, and electrodes for MHD generation units.

The development of CMC technology is critically related to the contemporary advances in ceramic science and fibre fabrication technology, as the versatality and performance of CMC components are limited by the properties of the two major constituents - matrix and reinforcement materials. The current diffusion of CMC technology to industries and other technologies is gradual, but several issues are readily noticeable. Successful commercial applications of the CMC technology and products will require substantial innovative developments in engineering design, quality assurance, manufacturing processes and tooling. The latter three are particularly important for high-volume production of parts with consistent quality and reasonably low cost. There is also the need for novel joining technology for CMC parts with components made of other materials as dictated by engineering designs.

Metal Matrix Composites

Metal matrix composites (MMCs) consist of metal alloys reinforced with fibres, whiskers, particulates and wires. Development of metal matrix composites began over 20 years ago. However, early MMC systems found few applications. The first major MMC structural system was boron/aluminum, developed in the late 1960's. With recent development of new MMC systems, offering superior mechanical properties and unique physical characteristics such as low thermal expansion, insensitivity to moisture and high temperature strength properties, interest in MMCs has been revived.

The present dominant metal matrix materials are aluminum, magnesium, titanium and their alloys. Aluminum, magnesium and their alloys are known for their low density and are useful for applications for which weight saving is important e.g., airplanes, space vehicles etc. However, titanium and its alloys have a high melting temperature and are used where high temperature capability is required. Compared to the polymer matrix composites, metal matrix has other advantages such as higher temperature capability, higher transverse stiffness and strength, higher shear moduli, higher electrical and thermal conductivities, better radiation and fire resistance, and no moisture absorption.

For reinforcements, the key fibres used at present are boron, beryllium, graphite, alumina and silicon carbide. All of these fibres have high tensile strength which make them extremely suitable as reinforcing agents for composites used for structural applications. While whiskers and particulate reinforcements are normally inferior in mechanical properties compared to their fibre counterparts, more isotropic properties are attained.

Compared to metals, MMCs have impressive properties. They have higher strength-to-density and stiffness-to-density ratios, better fatigue resistance, lower coefficient of thermal expansion and better wear resistance. The technology is still in its infancy, however, and commercial applications are extremely limited. A list of manufacturers of MMCs is given in Table 9; it is readily seen that the reinforcements are either silicon carbide or alumina.

In the automotive industry, Toyota has already employed alumina/aluminum composite as connecting rod material in its newest showcar (FX-1); this composite has strength equivalent to steel but low density. In sports applications, boron/aluminum, graphite/aluminum and silicon carbide/aluminum are used in making tennis rackets, skis, golf clubs, bicycle frames and fishing rods. Notwithstanding these examples, the principal applications for MMCs are in the military and space equipment systems. A barrier to the increased use of MMCs in commercial sector is the lack of in-service experience and performance data. Cost

TABLE 9

List of Manufacturers of Some Metal Matrix Composites Containing Advanced Ceramics Reinforcement

Company	Product	Annual Production or Production Capability	Price ($ U.S.)
DWA	SiC/Al	20 000 lb./year	$50/lb.-1000 lb. basis
	Al_2O_3/Al	100 lb./year	$20/lb.-10 000 lb. basis
ARCO Chemical	SiC/Al	Not available	$70-100/lb.
American Inc.	SiC/Al	Research Quantity	$300-400/lb.
	Al_2O_3/Al	Research Quantity	Not available
AVCO	SiC/Al	Research Quantity	No available
	Al_2O_3/Al		
Superior Graphite Co	SiC/Al	200 000 lb./yr	$1-15/lb. depending on grade
Mitsubishi Al.Co.	SiC/Al	Research Quantity	$200/lb.

is also another prime factor inhibiting the use of MMCs in other areas.

Research is continuing on improving the physical and mechanical properties of reinforcements, and to develop new MMC systems. New technology such as rapid solidification, is being considered to improve properties to an even greter extent. For example, rapidly solidified silicon carbide/aluminum produces a uniform distribution of non-shearable dispersoids such as AlSi, which stabilizes grain boundaries thus providing high-temperature properties.

Other new systems include "hybrids", which use either more than one type of reinforcing fibre in a single matrix, or a foil on the MMC of a different composition to that of the matrix. Other types of hybrid systems include graphite/aluminum cross-piled with boron/aluminum, and graphite and alumina fibres that have been formed into a single yarn and infiltrated with aluminum. In the latter example, the graphite provides increased compressive strength.

In general, it can be stated that with improvements in, and availability of, new and/or improved advanced ceramic reinforcing materials, the development and use of MMCs will increase.

4.4.3 Status of Process and Manufacturing Technology

The status of process and manufacturing technology for the production of advanced structural ceramics has been summarized by Professor H.K. Bowen of M.I.T as follows: " The major over-riding problem of high performance ceramics is that the components with the desired properties and microstructure cannot be reliably and reproducibly produced." The essential origin of this lack of reliability resides in the extreme sensitivity of several important properties to relatively small scale microstructural heterogeneities, coupled with a generally inadequate control of microstructure evolution during processing. The mechanical failure of ceramics occurs from large microstructural defects. The avoidance of "large microstructural defects" thus constitutes the primary requirement for the processing of ceramics with superior mechanical reliability.

The primary route for the development of useful ceramic components employs solid state reaction processes, dependent on the compaction and densification of ceramic powders. Sequential processes are used for the generation of these powders, their assembly into the desired shape, and their consolidation into the final product. In contrast to processing methods used for most other materials, this sequential process has the unique characteristic that the desired final material/product is generally made after, rather than before, a forming /shaping step. As a consequence, the preparation and handling of particulate matter throughout these sequential processes are of dominant concern in meeting the final objective of the finished article.

A simplified view of the ceramic production processes is given in Figure 5. The process technology can be divided into four steps:

- Body preparation
- Forming and shaping
- Densification
- Finishing and joining
- Non-destructive testing and inspection

Body Preparation

In general, the ceramic raw materials in the form of powders are mixed with the required additives such as binders, deflocculation and/ or sintering aids. The mixing can be dry or ina slurry, in which case it is spray-dried. For advanced ceramics production, the general tendency is to use slurry procedures for mixing the powders followed by controlled spray-drying techniques to obtain the desired powder in terms of particle size and flow characteristics.

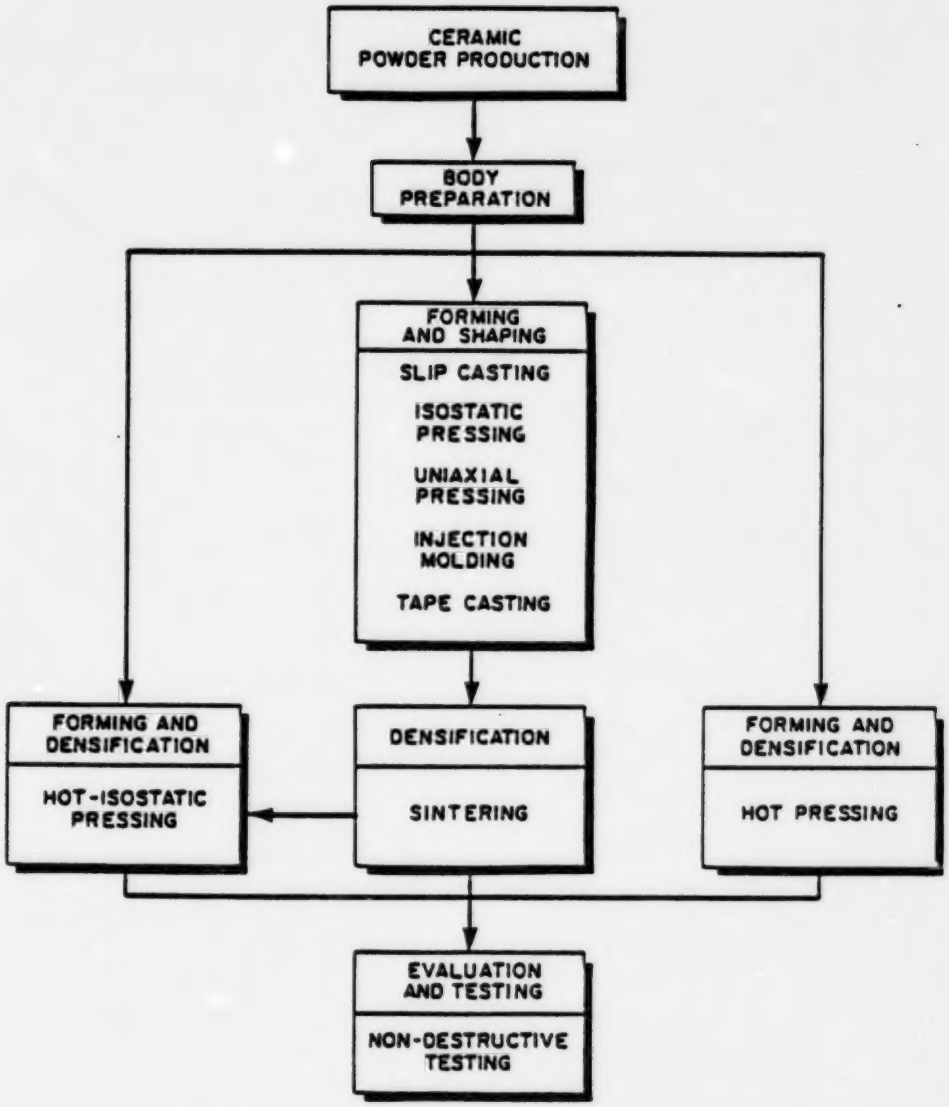


Figure 5. Ceramic Production Processes Used in the Manufacture of Advanced Ceramics

Mixing the powders to obtain a homogeneous and uniform body is a very crucial step because any defects/impurities introduced in this step are carried into the final product. Furthermore, since finer (sub-micron) powders are used in the preparation of the body, the use of sophisticated mixing equipment and control procedures become imperative. The process equipment and technology are being continuously improved to meet the increasing demands in terms of quality and yield; increased rejection rate is particularly damaging in terms of manufacturing cost. Sintered ceramics cannot be reprocessed in contrast to metals and plastics processing, where the material can usually be recycled. Since fine ceramic powders are expensive to begin with, it is evident that optimum body preparation processes are important.

Forming and Shaping

The four common forming and shaping techniques used are: uniaxial pressing, slip casting, isostatic pressing and injection molding. All these methods are used in forming advanced structural ceramics. However, in general, uniaxial pressing is limited only to very simple shapes; the other forming techniques are used more commonly because complex shapes can be formed.

The application of slip casting and injection molding techniques for the manufacture of advanced structural ceramics is receiving considerable R&D effort because of their usefulness in forming complicated shapes e.g., turbocharger rotors, turbine blades, pre-combustion chambers etc. Also, these processes yield near-net shapes which reduce machining time and cost.

Densification

The green ceramic articles are produced in the shaping/forming process contain moisture and/or binders. The moisture is removed by drying in controlled humidity environment. The binders are removed by heating in a furnace at low temperatures (400-500 °C), followed by a high temperature densification process, usually called "sintering". The ultimate goal of sintering is to achieve near theoretical density and the desired microstructure.

Sintering is the primary method for converting loosely bonded powder into a dense body. It involves consolidation of the ceramic powder by diffusion on an atomic scale at high temperatures in the range 1000-2200 °C, depending upon the material composition. Oxide ceramics are easy to sinter, and the sintering temperatures are relativey low - in the range 1600-1800 °C. Non-oxide ceramics such as silicon carbide and silicon nitride are difficult to sinter to high densities and much higher temperatures (2000-2200 °C) are required. The reason for this difficulty has been attributed to two mechanisms: (i) vacancy diffusion is strongly inhibited by the directional

chemical bonding (co-valent) in these materials; and (ii) surface diffusion or vapour transport in these materials largely dominate transport mechanisms at all temperatures and prevents densification as a result of grain coarsening. Hence, sintering aids such as magnesium and yttrium oxides are used to promote liquid phase sintering.

The term "microstructure" describes three characteristics of the finished ceramic. They are: the number and identification of the phases present; the relative amounts of each phase present; and characteristics of each phase such as composition, size, shape and orientation. For a given composition, the microstructure is very sensitive to heat treatment parameters such as heating rate, sintering temperature, soaking time, cooling rate etc. Hence, for each material combination i.e., starting ceramic powders, it is necessary to establish optimum sintering conditions to achieve the desired microstructure. The term "grain-boundary engineering" or "microstructural engineering" is used to describe the complex aspects of ceramic processing required to achieve the desired microstructures.

Hot pressing (HP) and hot-isostatic pressing (HIP) techniques are special techniques which combine shaping and sintering processes into one step. Uniaxial hot pressing is used to reduce grain growth, eliminate porosity, and densify ceramics that do not sinter easily. This method is used in the manufacture of ceramic cutting tools, electronic ceramic components, and microwave absorbing ceramics. This method is best suited for simple shapes and small size.

In the hot-isostatic pressing process, an inert gas such as argon is used to apply pressure uniformly and equally in all directions at elevated temperatures. Hence, complex shapes can be fabricated. The advantages of the HIP processes are: greater microstructural control which ensures improved mechanical properties and better surface finish; near-net shape forming; lower cost (relative); densification of materials and compositions that cannot be otherwise fabricated; and better uniformity within the parts as well as part to part. This technology is well established in the fabrication of metals by powder metallurgical techniques, however, in the case of advanced ceramics, the applications are still evolving - primarily becuase the market for high-volume high-performance components is inadequate for the required business decisions. HIP techniques can be combined with normal pressureless sintering technology to achieve defect-free components with high density and superior properties. Commercial equipment is available from ASEA (Sweden), Kobe Steel (Japan), Gorham (USA), and Vacuum Industries (USA).

Finishing

In all high performance applications, advanced ceramics are used as components to meet specific functions. Hence, they have to meet

stringent dimensional specifications. During the manufacturing process ceramic undergo shrinkage which is usually taken into account in dimensional design of the die. However, it is necessary to "finish" the components by grinding and/or polishing to meet the dimensional specifications. Since advanced ceramics are characterized by high density and hardness, it is necassary to use diamond grinding/polishing techniques to achievethe required tolerances. This is an expensive process. It is estimated that the finishing costs can amount to as much as 15-20 per cent of the final cost (Table 10). Hence, considerable R&D effort is devoted to develop manufacturing techniques to obtain "near-net" shape components to reduce/eliminate finishing costs.

Non-destructive Testing and Inspection

Ceramics are brittle materials and failure occurs catastrophically compmared to metals. Hence, advanced ceramic components for structural applications have to meet stringent mechanical property requirements, particularly strength and toughness. Fracture in brittle solids occurs either by direct extension of a single pre-existant flaw (from the large extreme of the population), or by the coalescence of small flaws. The flaws that ultimately initiate a fracture in brittle solids, such as ceramics, are classified into two categories, namely, intrinsic and extrinsic. The intrinsic flaws are introduced during the fabrication of the ceramic and are predominantly inclusions and/or voids. The extrinsic flaws are stress induced cracks, such as surface cracks introduced during grinding and polishing operations, and the microcracks that result from large scale residual stresses.

Non-destructive testing techniques, based on a number of different scientific principles, are being developed to detect and characterize the flaws so that their behaviour in the relevant application can be predicted. Surface wave techniques are used to predict failures by surface cracks. The characterization of bulk defects is more difficult and complex. Some of the techniques that are being perfected are scanning laser acoustic microscope and other bulk wave techniques. To date no satisfactory commercially cost-effective method is available.

The cost of inspection and rejection after manufacture of the components is estimated to be in the range 40-50% (Table 10). Hence, intensive R&D is in progress not only to improve manufacturing techniques but also to develop reliable inspection and testing equipment and procedures.

TABLE 10

Manufacturing Costs in High-Performance Materials

Process	Structural Ceramics(%)	Metals & Others(%)
Starting Materials	5 - 10	5 - 10
Physical Processing	5 - 10	10 - 20
Chemical Processing	10 - 20 (optional)	20 - 30 (high temp)
Shaping	5 - 10	10 - 20
Thermochemical processing	15 - 20	5 - 10
Finishing	15 - 20	5 - 10
Inspection & rejection	40 - 50	5 - 10

(After J.C.Agarwal, Adv.Cer.Mat, Vol 1, NO 4, 1986)

4.4.4 Status of Advanced Ceramic Powders

Virtually all the processes that occur throughout the processing cycle in the manufacture of advanced structural ceramics depend upon the characteristics and properties of the starting ceramic powders. There is general consensus in the technical community that the characteristics of the starting powders ultimately control the properties of the finished product. The desirable features in ceramic powders required for the processing of advanced ceramics are: (i) high purity; (ii) non-agglomeration; (iii) spherical geometry; and (iv) high reactivity. Unfortunately, there is no direct correlation between measured properties of a powder and its behaviour in giving the required properties to the ceramic. This problem is particularly acute from the point of view of powder producers because the ceramics manufacturers expect them to supply "good" powders.

High purity. sub-micron powders are now considered mandatory for preparing advanced ceramics, principally because their extensive surface area enhances sinterability. These powders cannot be obtained from naturally occuring minerals by grinding and beneficiation for two reasons. Firstly, the minerals that can yield the desired chemical composition and purity do not occur in nature; and, secondly, the required particle characteristics cannot be obtained by physical grinding techniques.

Various methods for synthesizing both oxide and non-oxide ceramic powders are emerging. To obtain better process control, these methods generally involve chemical reactions in the gas or liquid phase. These methods are listed in Table 11. For each required powder, a number of alternative processes exist. The selection of the most appropriate cost-effective process to achieve the required properties is the key to success.

The ceramic powder requirements can be divided into two groups as follows:

- Technical Requirements
- Cost Requirements

Technical Requirements

The general powder quality requirements are:

Quality	Requirements
Powder Fineness	Sub-micron size; narrow size distribution; high surface area (10-20 m^2/g)

TABLE 11

Chemical Techniques Used in the Preparation of Advanced Ceramic Powders

Powder Preparation Processes

Process	Ceramics	Comments
Pyrolysis of Organometallics	Oxides Carbides Nitrides Borides	Shows promise for future
Nitridation and Carbothermic Reduction	Nitrides Carbides	Has wide applicability
Chemical Vapour Deposition	Oxides Carbides Nitrides Borides Glasses	Thermal, plasma and laser assisted Good process control Particles are usually ≤ 0.1 μm, and clustered or bonded together
Nonaqueous processing and calcination	Non-oxide powders	Shows promise for the future
Metal salt decomposition, freeze drying, and calcination	Oxide powders	Has wide applicability
Pressure precipitation	Oxide powders	An unexploited technology having wide potential
Hydrolytic decomposition	Oxide powders	Can produce ultrafine high purity powders
Sol-gel process	Oxide powders	Particle size can be varied substantially

Powder Morphology	Spherical geometry;
Phase Composition	Required crystalline phases Required crystallite size High lattice defects
Purity	High purity Minimum concentration of undesirable impurities (ppm)
Physical State	Minimum agglomeration High packing density
Sinterability	High reactivity Shrinkage and density

Although the foregoing parameters are important, and are used in writing specifications, in practice the powders are evaluated in the laboratory using chosen process parameters to suit the given product line. This is due to the interdependence between powder properties and processing steps. A very close working relationship between the powder producer and the ceramics manufacturer is usually required to minimize the difficulties in the selection of the most suitable powder.

Cost Requirements

The unique properties of advanced ceramics, by themselves, do not guarantee their future market success. Their success depends upon their cost relative to competing materials such as steel, polymers and composites. The cost of the ceramic powders, therefore, will play a very important role in the market acceptance of these advanced ceramic materials.

At present, the costs of silicon carbide, silicon nitride, sialon, alumina and zirconia powders are high. Therefore, these materials are used only where performance/cost benefits can be justified. Typical price ranges for these materials are given below:

Material	Cost (Cdn $/kg)
α- SiC	30 - 90
β- SiC	same as above
α- Si_3N_4	90 - 110
ZrO_2	50 - 60
Al_2O_3	60 - 80

Recently, Agarwal(*) has discussed the economics of powder production. If the objective of a company is to achieve US$20 million in sales by the year 1995, it can be achieved by selecting specialyty products. The estimated capital costs, operating costs and profitability are given in Table 12a. Capital costs for chemical synthetic processes are expected to be much higher than for high-temperature processes, however, they are considered to be advantageous in the long run because they give powders of the required quality. Since the production of powders is expected to be dominated by big chemical producers, the opportunities for small producers are expected to be "niche" markets and specialty powders.

The investment required for sales of US$ 500 million by the year 1995 is shown in Table 12b. The investment requirements are expected to be large because of the scaled up operations. Profits, however, are also expected to be large. Nevertheless, two difficulties are projected: finding a large manufacturer who, in turn, has to find large users. Hence, in the early years, the plant is expected to operate at low capacity and profitability until the ultimate large production is achieved.

The projected decrease in capital and operating costs with increased capacity of the plant is given in Table 12c. The problems faced by the powder producers (existing as well as new comers to industry) are the uncertainities involved in the business decisions. The two important uncertainities are: (i) the standards and specifications for the powders are not yet established and, therefore, it is difficult to firm up the production processes; and (ii) the demand for the powders depend upon the market penetration rate of the components which, to a large extent, depends upon business decisions of the component users.

The ceramic powders of interest in the manufacture of advanced structural ceramics for bulk of the major applications are:

- Silicon carbide
- Silicon nitride
- Sialons
- Zirconia
- Alumina
- Boron nitride
- Boron carbide
- Others (other hard carbides, borides, and nitrides)

The technology and commercial status of these powders will be discussed in some detail.

---

* "Process Economics and Strategies in the Advanced Ceramics Industry". J. C.Agarwal. Adv.Cer.Mat. Vol 1, No.4, 1986.

TABLE 12

Economics of Advanced Ceramics Production

12a. Objective: US$ 20 Million Sales by 1995

Powder*	Capital ($ million)	Operating $/kg	Profitability before tax (%)
Low-temp. chemical	10–20	15–22	25–40
High-temp. chemical	7–15	15–22	20–30
Components†	10–20	4–9	25–30

*Powder business has large technical risks. †Component business needs market development.

12b. Objective: US$ 500 Million Sales by 1995

Range– $ investment/$ of sales		Profitability before tax (%)	Comments
Powders or starting material	0.50–1.00	20–40	High front-end investment
Components	0.25–0.50	20–30	High working capital
Systems	0.10–0.20	10–15	Long lag time

12c. Economy of Scale up in Production

Capacity (million kg/yr)	Capital ($ millions)	Operating costs ($/kg)
1	12–17	13–19
10	60–90	3–4
100	300–450	0.5–0.6

Silicon Carbide Powders

Silicon carbide exists in two polymorphic modifications, namely, α-SiC which is cubic, and β-SiC which is hexagonal. The α-SiC, made by the Acheson process was the only commercial source for many decades, and has been used for the manufacture of abrasives, refractory products and refining of steel for more than 75 years. Special grades of α-SiC powders, obtained by grinding and beneficiation of the crude commercial material, have been used in the manufacture of silicon carbide based advanced ceramics since the early 1970's. The quantities, however, are relatively small compared to the total annual world tonnage (*) and are estimated to be about the 5,000-7,000 tons per year. It is now generally recognized that this material has a number of disadvantages as a starting material in terms of the required properties e.g., purity, particle morphology. β-SiC powers are the preferred powders because they give higher strength products.

Almost all silicon carbide based advanced ceramics are now manufactured from α-SiC produced by the Acheson process because it is readily available and process technology has been developed around this material(**). In North America, both Norton Co and Sohio Engineered Materials Co., manufacture α-SiC powders and use them in-house for the production of ceramic components; the powders are not sold in the open market. However, the powders are manufactured and sold commercially in Japan and W.Germany. A list of manufacturers is given in Table 13 and a typical flow sheet is shown in Figure 6.

β-SiC powders have a number of advantages over α-SiC powders for the manufacture of advanced ceramics, because these powders can be synthesized to give very high purity and, more importantly, very fine particle size and high surface area; the latter property gives the powder high reactivity. The synthesis methods for β-SiC powders can be grouped into two categories:

- Vapour phase methods
- Carbothermic methods

(*) The tonnage used for industrial and engineering applications is estimated to be about 5000-7000 tons/year compared to total annual production of about 360,000 tons (1982); the rest of the material is used as abrasives, refractories, kiln furniture, metallurgical applications etc.

(**) In Japan, β-SiC has been commercially available for some time and is likely used in the manufacture of advanced ceramics. Commercial information is not available.

TABLE 13

List of Manufacturers of α-SiC and β-SiC Powders

NAME OF COMPANY	COUNTRY	PRODUCTS	
Advanced Refractories	USA	α-SiC	β-SiC
Norton Co	USA	α-SiC	
Sohio Engineered Mat	USA	α-SiC	
Ferro Industries	USA	α-SiC	
Superior Graphite	USA		β-SiC
ESK	W.Germany	α-SiC	
Lonza	W.Germany	α-SiC	
H.C. Starck	W.Germany	α-SiC	
Showa Denko	Japan	α-Sic	β-SiC
Ibiden	Japan	α-SiC	β-SiC
Shinetsu Chem	Japan	α-SiC	
Taiheiyo Random	Japan	α-SiC	
Shinano Denki	Japan	α-Sic	
Fukushima Denko	Japan	α-SiC	
Fujimi Kenmazai	Japan	α-SiC	

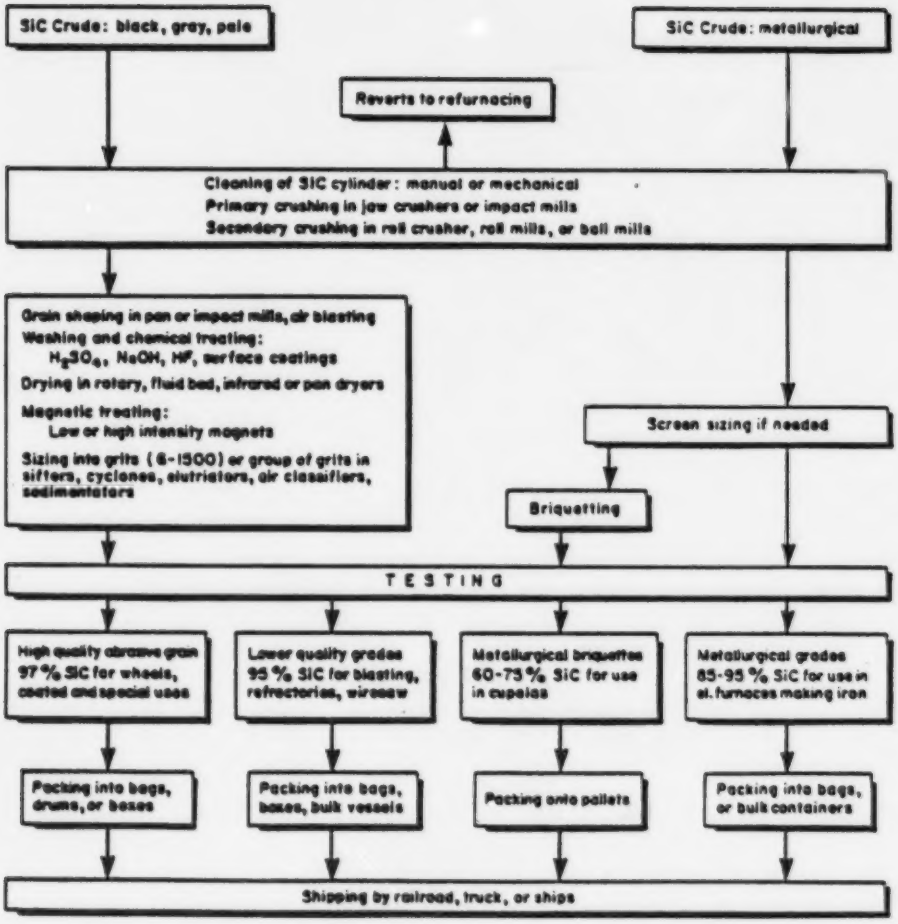

SiC Crude: black, gray, pale
SiC Crude: metallurgical
Reverts to refurnacing
Cleaning of SiC cylinder: manual or mechanical
Primary crushing in jaw crushers or impact mills
Secondary crushing in roll crusher, roll mills, or ball mills
Grain shaping in pan or impact mills, air blasting
Washing and chemical treating:
H_2SO_4, NaOH, HF, surface coatings
Drying in rotary, fluid bed, infrared or pan dryers
Magnetic treating:
Low or high intensity magnets
Sizing into grits (6-1500) or group of grits in sifters, cyclones, elutriators, air classifiers, sedimentators
Screen sizing if needed
Briquetting
TESTING
High quality abrasive grain 97 % SiC for wheels, coated and special uses
Lower quality grades 95 % SiC for blasting, refractories, wiresaw
Metallurgical briquettes 60-75 % SiC for use in cupolas
Metallurgical grades 85-95 % SiC for use in el. furnaces making iron
Packing into bags, drums, or boxes
Packing into bags, boxes, bulk vessels
Packing onto pallets
Packing into bags, or bulk containers
Shipping by railroad, truck, or ships

Figure 6. Typical Flow Sheet Representing the Processing Steps Used in Manufacturing α-SiC Grains and Powders

Silicon Nitride Powders (Si_3N_4)

Silicon nitride, like silicon carbide, exists in two polymorphic forms, alpha and beta, both of which have a hexagonal structure. The beta-phase appears to be thermodynamically the more stable, although the alpha-phase is more commonly formed in vapour phase or low temperature reactions. The alpha-pase to beta-phase reconstuctive transformation takes place readily in the presence of a suitable liquid phase at high temperatures. Like silicon carbide, silicon nitride is also a covalent material. Hence, the manufacture of high-density high-strength ceramic components requires powders with special properties and characteristics which are listed below:

Chemical Purity

The chemical purity of the powders has to be very high, particularly with respect to metallic impurities which should not exceed 0.1%. The oxygen content of the powder - usually present as silica surface layer on the powder particles - should be low, in the range 1-2%.

Particle and Phase Requirements

The silicon nitride powder should satisfy the following particle size requirements:

Phase type: > 90% alpha
High surface area: > 20 m^2/g
Small grain size: 0.1 to 0.5 microns
Minimum agglomeration
Spherical particle shape
Tap density of 0.6 to 0.9 gm/cm^3

Three techniques are currently used for the commercial manufacture of silicon nitride powders:

Nitridation of Metallic Silicon Powder

This process depends upon the high temperature reaction of silicon vapour with nitrogen, and has been extensively developed as a standard process in many countries, particularly W.Germany and Sweden. The process used by H.C.Starck in W.Germany is shown in Figure 7. The chemical and physical properties of five grades of powders manufactured by this company are listed in Table 14.

Carbothermic Reduction of Silica

In this process, a mixture of fine silica and carbon is reacted with nitrogen at high temperatures. The reaction is harder to control

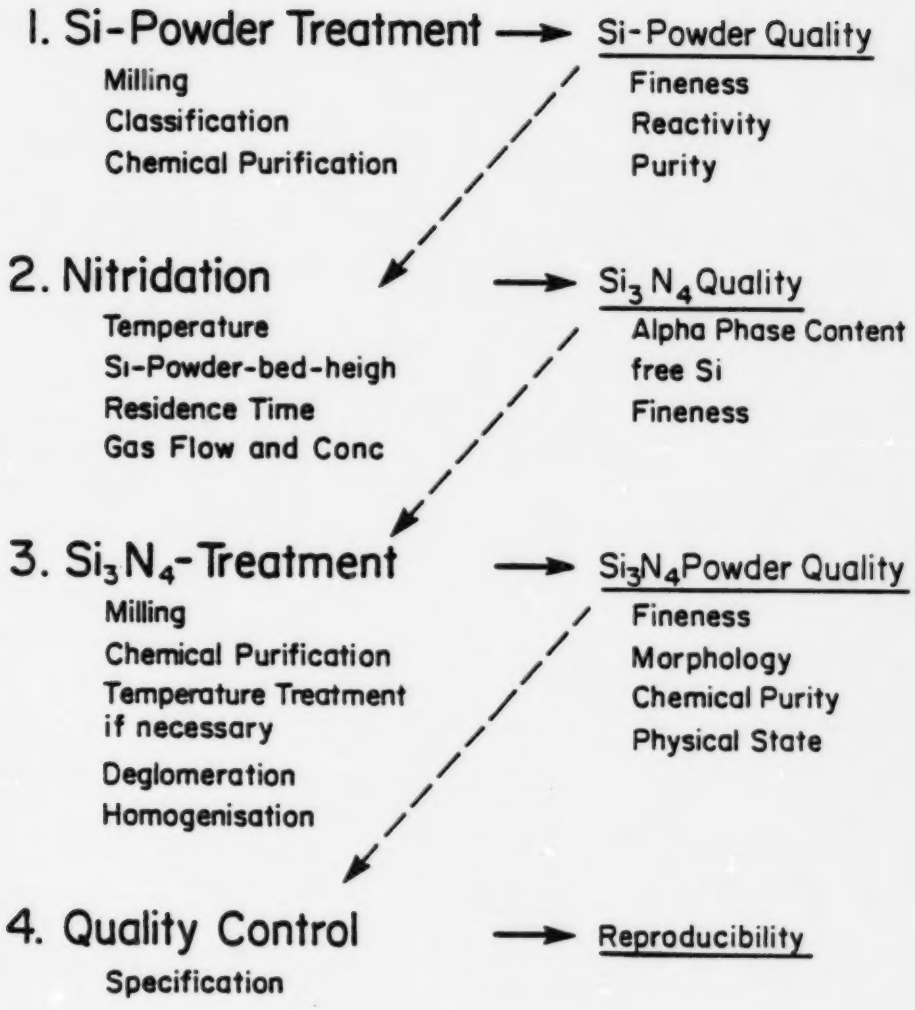


Figure 7. H.C.Starck Co Process for the Manufacture of α-Silicon Nitride Powders

TABLE 14

Properties and Characteristics of α-Silicon Nitride Powders Manufactured by H.C.Starck Co, W.Germany

Powder Grade	Fineness		Phases			Impurities				
	Specific Surface Area (BET) m^2/g	ø Grain-Size (FSSS) µm	Beta-Si_3N_4 %	Free Si %	calcul. SiO_2 %	O %	C %	Fe %	Al %	Ca %
H 2	4	1,4	4	0,2	2,4	1,3	0,4	0,08	0,15	0,04
H 1	9	0,7	4	<0,1	2,4	1,3	0,4	0,04	0,10	0,03
LC 1	9	0,7	3	<0,1	2,4	1,3	0,1	0,04	0,10	0,03
LC 10	15	0,5	3	<0,1	2,8	1,5	0,1	0,03	0,08	0,02
LC 12	23	0,4	3	<0,1	3,2	1,7	0,1	0,02	0,06	0,01

from the point of view of contamination of the product by impurities such as carbon, oxygen and silicon carbide. Toshiba corporation of Japan is reported to have solved the impurity problem and uses this route for the manufacture of silicon nitride powders. Tateho Chemicals Co., of Japan is also reported to be manufacturing by this method. The Toahiba process, which is available for licencing, is illustrated in Figure 8.

Vapour Phase Processes

Silicon nitride powders have been prepared using vapour phase reactions between gaseous silicon containing compounds such as silicon tetrachloride or silane and ammonia as the source of nitrogen. The chemical reactions can be represented as follows:

$$3\ SiCl_4 + 4\ NH_3 \text{ ---------- } Si_3N_4 + 12\ HCl \quad (i)$$

$$3\ SiCl_4 + 16\ NH_3 \text{ ---------- } Si_3N_4 + 12\ NH_4Cl \quad (ii)$$

$$3\ SiH_4 + 4\ NH_3 \text{ ---------- } Si_3N_4 + 6\ H_2 \quad (iii)$$

GTE Sylvania in the USA is using reaction (i) for the manufacture of silicon nitride powders. All of its production is used in-house for the manufacture of cutting tools and specialized engineering components. Ube Industries and Toyo Soda in Japan are using a modified process based on reaction (ii) which involves the reaction between silicon tetrachloride and liquid ammonia. A schematic of this process is given in Figure 9.

Silicon nitride powder is now commercially available in Japan, W.Germany and Sweden. It is manufactured by some companies in the USA for internal production but not for sale. The world manufacturers and suppliers are listed in Table 15.

Sialon Powders ($Si_{6-x}Al_xSi_{8-x}O_x$)

Sialon family of materials are produced by replacing silicon and nitrogen in Si_3N_4 by aluminum and oxygen, respectively. These ceramics are made by reacting the required proportions of silicon nitride, aluminum nitride, alumina and silica to obtain the desired ultimate composition as shown in Figure 10.

The exact compositions and the method of manufacture are protected by patents. However, Lucas Cookson has licenced the process to many manufacturers.

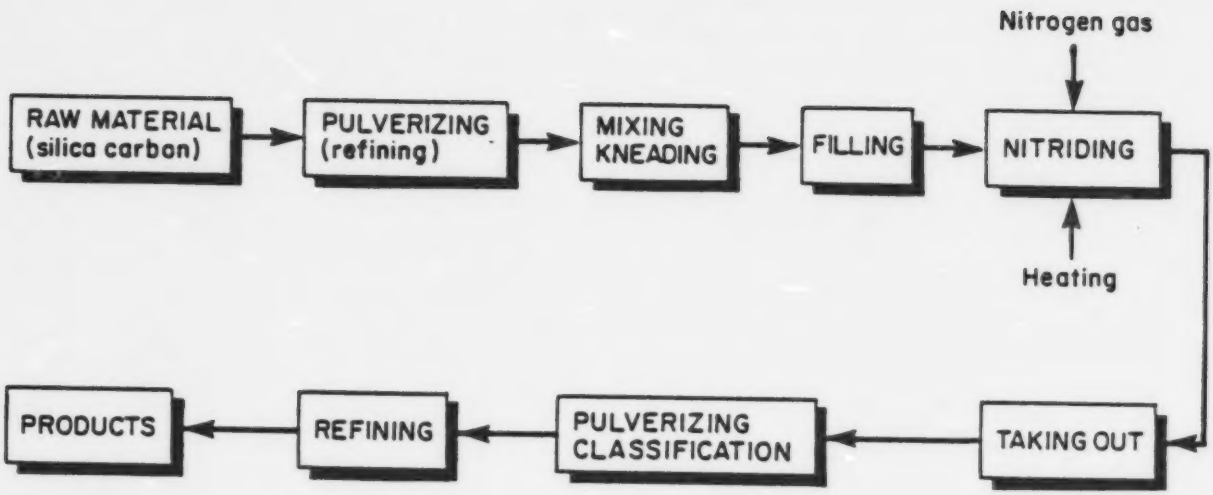


Figure 8. Schematic of the Process for the Manufacture of Silicon Nitride Powders by Carbothermic Reaction between Silica, Carbon and nitrogen - Toshiba Process

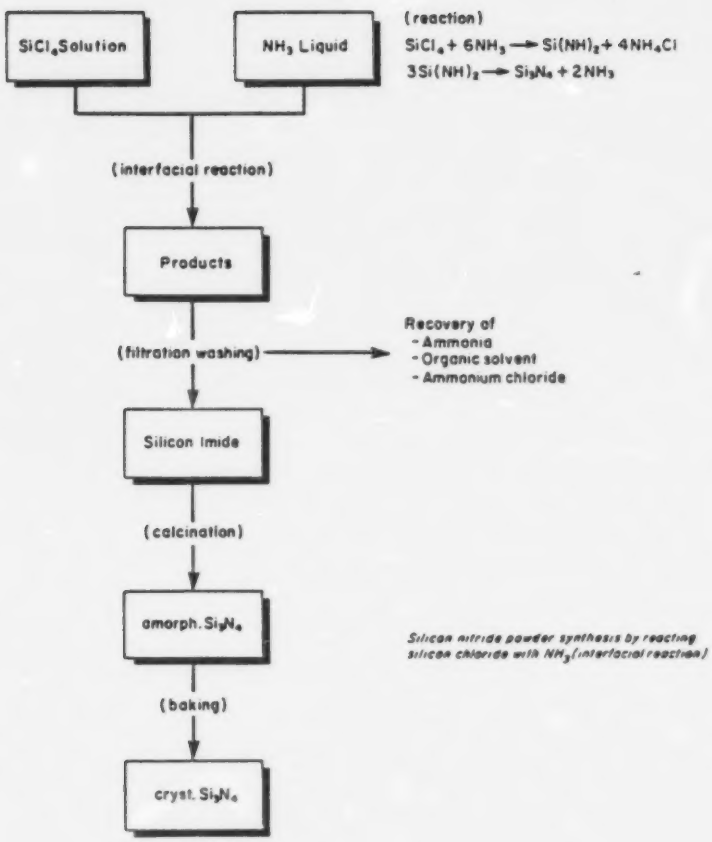


Figure 9. Schematic of Process for Producing Silion Nitride Powders from Silicon Tetrachloride and Ammonia

TABLE 15

Commercial Manufacturers and Suppliers of Silicon Nitride Powders

Country	Company	Production Capacity	
		α-Si_3N_4	β-Si_3N_4
Japan	Denki Kagaku	7,800 kg/m	12,500 kg/m
	Starck Japan	2,500 kg/m	-
	Nihon Denko	1,000 kg/m	1,800 kg/m
	Ube Industries Ltd	1,000 kg/m	-
	Toshiba Ceramics	950 kg/m	-
	Showa Denko	800 kg/m	-
	Toyo Soda	750 kg/m	-
	Shinetsu Kagaku	600 kg/m	-
	Nihon Kokan	NA	NA
	Onoda Cement	NA	NA
	Toray	NA	NA
	Kyoritsu Yogyo	NA	NA
W.Germany	H.C.Starck	40 tons/yr	
Sweden	KemaNord Indstrichem	NA	
USA	GTE Sylvania	NA	
USA (Suppliers)	Ube Industries,Ltd	NA	
	Denki Kagaku	NA	
	KemaNord	NA	
	Toshiba	NA	
England	Morgan Matroc (Advanced Materials Engineering Ltd)	NA	

Source: Mitsui Toatsu Chemical Inc, through Dr.M.Bergeron, DRIE, Ottawa

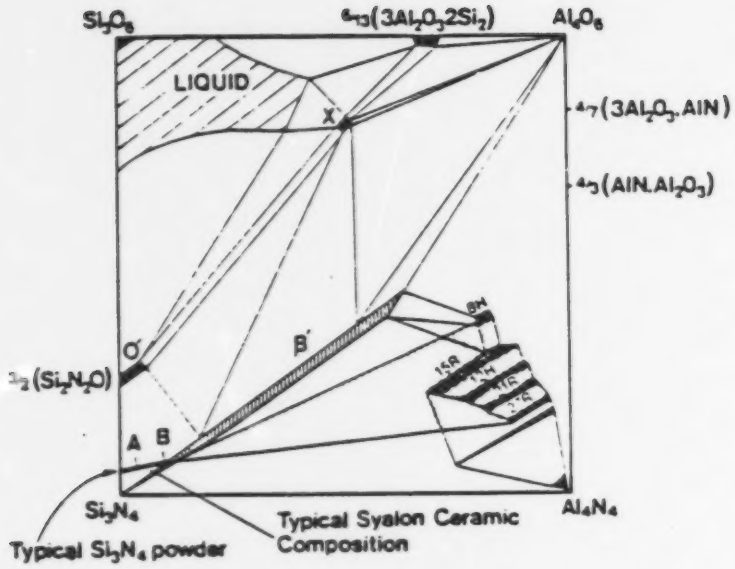


Figure 10. Typical Syalon Ceramic Compositions

Aluminum Nitride Powders

Aluminum nitride ceramics have become important in recent years as substrate materials for microelectronic circuitry becuase of their high thermal conductivity, very low electrical conductivity and a low thermal expansion coefficient. The purity of the powder is very important because it governs the first two properties. Sub-micron powders with size in the range 0.1 to 0.5 μm and high surface area are required for the fabrication of high density parts and components.

The conventional method for the production of AlN powders is through simultaneous carbothermic reduction and nitridation of alumina. Toshiba Corporation in Japan is using this method for commercial production.

Aluminum nitride powders can also be produced by the direct nitridation of aluminum metal. It is not clear if any of the commercially available powders are produced by this route.

Other methods under development include: reaction between alkyl aluminum (trimethyl aluminum or triethyl aluminum) with ammonia; and gas phase nitridation of a mixture of aluminum and aluminum trichloride ($AlCl_3$).

Boron Nitride (BN)

Boron nitride occurs in four polymorphic modifications. The hexagonal phase, which is often called "white graphite", is considered the most attractive material for many high-temperature applications because of its high thermal conductivity, chemical resistance, excellent electrical resistance, resistance to oxidation up to 900 ^{o}C, and resistance to most metals and salts.

Boron nitride is prepared by the reaction between boron trioxide (B_2O_3) and nitrogen or nitrogen containing compounds such as urea or melamine.

It is manufactured by a number of companies throughout the world e.g., Union Carbide in the USA and ESK in W. Germany.

Boron Carbide

Boron carbide is characterized by its extreme hardness and its very high neutron capture cross-section. It is manufactured by the carbothermic reduction of boric acid and the reaction can be represented as folllows:

$$4\ B_2O_3 + 14\ C \longrightarrow 2\ B_4C + 12\ CO$$

Boron carbide powder is manufactured by a number of manufacturers e.g., ESK in W.Germany for the in-house manufacture of ceramics. Hot pressing and/or hot-isostatic pressing techniques are used. Typical applications include:

- Nozzles for sand blasting
- Mortars for grinding hard materials
- Armour plates
- Cutting tools
- Neutron absorption

Zirconia Powders (ZrO_2)

Zirconia powders and chemicals are recovered commercially from two naturally occuring minerals: baddeleyite, the oxide mineral form; and zircon, a silicate whose composition is $ZrSiO$. Zirconia powders for manufacturing advanced ceramics for engineering applications are produced by two chemical techniques:

- Alkali fusion
- Alkoxide decomposition

The alkali fusion process is the most common method used for the manufacture of oxide and chemicals. The minerals are reacted with sodium hydroxide to form sodium zirconate. Pure zirconia is obtained from this material in two ways as shown in Figure 11. It is known that Toya Soda uses the oxychloride process.

Highest purity zicronia is made by the decomposition of zirconium containing organics such as zirconium alkoxides. This process also allows for tight control of particle size and distribution.

Many grades of zirconia powders are commercially produced for different applications. Pure zirconia powders (99.9%) are used to toughen other advanced ceramics such as alumina and silicon nitride. They cannot be used in the pure form in the manufacture of zirconia ceramics because of phase transformations accompanied by volume changes during thermal cycling. Hence, zirconia powders with the required amounts of stabilizing agents such as MgO and Y_2O_3 are commercially manufactured and sold. For example, Magnesium Elektron, the subsidiary of Alcan Aluminum Ltd., markets powders containing CaO, MgO and Y_2O_3 in the range 4-16 weight per cent. Toyo Soda of Japan markets a much larger range of powders in which Y_2O_3, Al_2O_3, MgO, and CeO_2 are incorporated homogeneously in the manufacturing process. The major manufacturers are listed in Table 16.

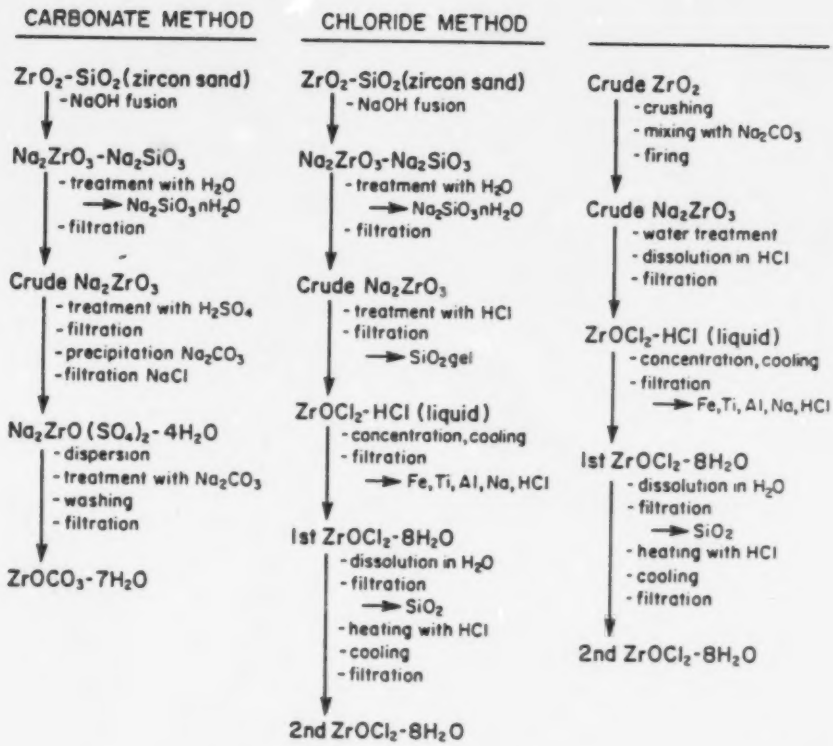


Figure 11. Carbonate and Chloride Methods for Producing Pure Zirconia from Ores

TABLE 16

Commercial Manufacturers and Supliers of ZrO_2 Powders

COUNTRY	COMPANY	PRODUCTION CAPACITY
Japan	Toyo Soda	4,000 kg/m
	Daiichi Kigenso	4,200 kg/m
	Shin Nihon Chem	1,000 kg/m
	Dowa Chem	800 kg/m
	Hokko Chem	600 kg/m
	Toray	12 tons/yr
	Starck Japan	NA
	Morimura	NA
	Kyoritsu Yogyo	NA
	Asahi Kasei	NA
W.Germany	H.C.Starck	NA
France	Criceram	NA
	Rhone-Poulenc Inc	NA
England	Magnesium Elektron	NA
	United Ceramics	NA
USA	Magnesium Elektron	NA
	Ferro Corporation	NA
	American Vermiculite	NA
	TAM Ceramics Inc	NA
	Harshaw Chemicals	NA
	Z-Tech Corp	NA
	Zircar	NA

High Purity Alumina Powders (Al_2O_3)

Advanced ceramics based on alumina require the use of very high purity alumina. The alumina powders that are currently available on the market usually have a purity greater than 99.99%. Industry, however, is being pushed to develop still higher purity materials - 99.999% to 99.9999% purity powders to satisfy increasing performance demands. Coupled with purity, the other requirements are fine particle size and narrow size distribution, typically less than 1 micron, and a narrow distribution of sizes in the range 0.5 to 1 micron.

There are six commercial production processes for high purity alumina. They are:

- Modified Bayer process
- Thermal cracking of ammonium alum
- Thermal cracking of ammonium aluminum carbonate
- Hydrolysis of organometallic compounds
- Ethylene chlorohydrin process
- Spark discharge process

The qualities of powder obtained by these processes are listed in Table 17. The commercial producers of high purity alumina are listed in Table 18. Japan has the largest number of producers and all the methods of production listed above are in use. France also has been a producer for many years. In the USA, high purity alumina up to 99.999% purity is also produced by a number of manufacturers.

The consumption of high purity alumina has been estimated at about 3000 tons per year, equally divided between USA, Japan and Europe. Prices for these high purity aluminas are very high. The Baikowski powder, manufactured in France, costs about US$ 30 per kg. (about Can$ 39). Because of the very high price, the 99.9999% purity material is used only in the manufacture of high-price products such as: transluscent tubes and envelopes for sodium lamps, substrates for MOS devices, and laser applications (ruby rods and YAG lasers).

The bulk of the ceramic products are manufactured from 99.99% purity powders.

TABLE 17

Properties of High Purity Alumina Powders Produced by Different Processes

		Sumitomo Chem Co.						Showa-Keikinzoku Co.			Iwatani Chem.			Sin-Nihon Chem. Co.
Grade		AKP-20	AKP-30	AKP-HP	A-HPS40	A-HPT	A-HPT-F	UA-5025	UA-5035	UA-5105	RA-40	RG-40	RK-40	L-30
Crystal Phase		"	"	"	"	"	"	"	"	"	"			"
Purity %		>99.99	>99.99	>99.995	>99.99	>99.99	>99.99				>99.99	>99.99	>99.99	99.98–99.995
Average Particle Size μm		0.5	0.4	0.4	0.4	0.4	0.3	0.4*	0.3*	0.25*	0.83	0.51	0.78	0.4**
BET m²/g		4–6	5–10	4–10	6–8	5–6	5–8	3	5	10	5.3	48.0	282.0	5–40
True Density g/cc								3.97	3.97	3.83	3.93	3.70	3.14	
Bulk Density		0.7–1.1	0.7–1.0	0.6–1.0	0.8	0.5	0.5	0.6	0.6	0.6	0.40	0.39	0.46	0.20–0.40
Tapped Density g/cc		1.1–1.5	1.1–1.5	0.9–1.3	1.2	1.2	1.2	1.0	1.0	1.0	0.95	0.93	0.95	0.40–0.80
Impurities ppm	Si	<40	<40	<8	10	8	8	6			<20			40
	Na	<10	<10	<3	20	15	15	10			%			65
	K							5						
	Mg	<10	<10	<3	<10	4	2	<1						
	Ca				10	2	2	<2						
	Fe	<20	<20	<8	7	7	7	4			25			60
	Cu	<10	<10	<3										
	Ca							<2						25
	Cr							<2						
Production Process		Hydrolysis of Organo-metallic Compound			Modified Bayer			Thermal cracking of alum			Spark Discharge			Ethylene Chlorohydrin

* α-Grain size ** by SEM

TABLE 18

Commercial Manufacturers and Suppliers of High Purity Alumina Powders

COUNTRY	COMPANY
Japan	Sumitomo Chem Co Showa-Keikinzoku Co Iwatani Chem Sin-Nihon Chem Co Nippon Light Metal (Shimuzu Works)
France	Baikowski Corporation Criceram Rhone-Poulenc, Inc
USA	Arco Chemical Co Alcoa Kaiser Chemicals Reynolds Alcan Chemicals
USA (Sales only)	Baikowski International Criceram Rhone-Poulenc, Inc
Canada	Alcan Chemicals

4.4.5 Sol-Gel Technology

It is now recognized that in the coming decades sol-gel technology will have revolutionary impact on the development and commercialization of advanced ceramics for both structural and functional applications. It is a versatile technology with very wide potential. It can be used not only for the synthesis of new ceramic powders required in the "ultrastructure" processing of advanced ceramics, but also in the development of monolithic ceramic components as well as for coating other materials and components.

There is little question that traditional processing methods do impose a severe limit on producing products of high reliability for use in severe environments. A new approach to producing components for electronic, structural, space and medical applications is needed for major advanced in the industrial application of advanced ceramics. "Ultrastructure" processing is recognized to be the key for realizing the full potential of advanced ceramics, monolithic as well as coatings. The goal of ultrastructure processing is the control of the surfaces and interfaces of materials during the earliest stages of production. Long term reliability of a material is usually limited by localized variations in the physical chemistry of the surfaces and interfaces within the material. The emphasis in ultrastructure processing is on limiting and controlling physical and chemical variablity by the production of uniquely homogeneous structures, extremely fine scale (100 Å) second phases, controlled surface compositional gradients, and unique combination of physical properties.

To date, sol-gel technology has been successfully used for the development of:

- New and novel glasses
- Crystalline ceramics with exceptional microstructure
- Coatings for the modification of electrical, optical, chemical and mechanical properties
- Ceramic powders with high chemical homogeneity and narrow distribution of particle size
- porous media with high surface area for catalyst and catalyst support applications
- matrix materials in ceramic-ceramic composites ranging from abrasives and fibres to glassceramics to films.

The word "sol" describes the dispersion of colloids in liquids; colloids, in turn, are described as solid particles with diameters in the range 10-1000 Å, each containing 10^3 - 10^9 atoms. When the viscosity of a sol increases sufficiently, usually through the partial loss of the liquid phase, it becomes rigid; this rigid material is termed a "gel". Gellling of a sol occurs either by electrolytic interaction of colloidal particles or by the formation of a polymeric network through chemical reactions.

In the sol-gel processing of ceramics, the products are formed by the growth of the material from a liquid solution or colloidal suspension of starting raw materials, such as metallic acids, chlorides, sulfates or nitrates, and metal alkoxides [$M(OR)_n$, where R is an alkyl and M is a metal with valence n].

Metal alkoxide systems, in comparison to colloidal systems, have several advantages. Because colloidal systems start out with particles, there is little control over both the sol and the gel microstructure. Hence, only particulates or powders can be produced, which must be melted or sintered into the bulk form.

Alkoxide systems, on the other hand, create a chemical polymerization through which the chemical bonds form while they are still in solution. Consequently, the gel volume depends on the degree of polymerization, as well as the hydrolysis conditions and polycondensation reactions. Hence, a monolithic structure is maintained. These critical parameters can be adjusted to control the microstructure and homogeneity, especially in the case of multicomponent compositions. Almost all of the oxides of group III and IV metals which make up the more common glass and ceramic compositions, can be prepared by this chemical method.

Two of the important applications are: coatings and porous solids.

Coatings

The dip coating technique has been successfully applied in the formation of many thin oxide films on glass. Some of these are amorphous and some are polycrystalline. The substrate is dipped into the sol-gel solution for a short time. After removal, the solvent is evaporated and hydrolysis and condensation follow. The film is then "hardened" by heat treatment at elevated temperatures. Since the density of the sol is usually not much greater than 1 gm/cm 3 , and that of the sol is usually much greater than 2-3 gm/cm ^{3} , very large shrinkages are experienced resulting in non-uniform thickness and mechanical cracking of the film. However, high quality films have been deposited on glass panes as large as 3 m x 3 m by this method and the products are sold commercially; Schott glass markets infrared

reflection-coated glass panes for superwindow construction.

Thick films can be made by repeated dip-coating. Indeed, transparent non-crystalline silica slabs of several milimeter thickness have been made by many dippings of an inert substrate into sol-gel solutions. After densification, these slabs are stable up to 1000 °C.

Porous Solids

It is well established that at temperatures not far above at which a sol has set to become a fairlt rigid gel, the gel is an extremely porous solid. The pores are inter-connecting i.e., opened. The porosity and pore-size distribution are dependent on the materials, catalyst, and temperature of reaction. In the silica gel, for instance, the pore diameters range from 20 to 80 Å, and the poroaity can be greater than 50%. Surface areas in excess of 900 m^2/gm have been reported for silica gels dried at 40 °C. Even after heating to a few hundred degrees, a great deal of the porosity is retained. The heat-treated gels are, therefore, good candidates for membranes and filters, particularly for gas-gas separation processes in the chemical industry. Other uses are as catalyst supports and catalyst themselves.

Porous alumina that is transparent and stable to 1200 °C has been reported; the interesting feature is that the porosity is as high as 63%. The material is machinable and has potential applications as a desicant and as a filter. It is believed that other polycrystalline oxide materials can be similarly fabricated into porous solids.

Perhaps the most porous solids with relatively high mechanical strengths are glass microballoons. Such microballoons can be fabricated with densities ranging from 0.15 to 0.38 g /cm^3 i.e., less than 10% of the bulk density of the glass. Diameters can be controlled from a controlled over the range 10-200 μm. Microballoons are now readily available from a number of industrial manufacturers, and have been used as light-weight fillers for plastics and synthetic foams. For a more sophisticated application, namely as a container of deutrium-tritium gaseous fuels for thermonuclear fusion experiments, glass microballoons of great uniformity have been prepared.

There is increasing interest in this technology for the development and manufacture of porous ceramics for use in gas-gas and liquid-liquid separations in the chemical industry.

4.4.6 Status of Advanced Ceramic Coatings

Historically, abrasion and wear resistant coatings were accepted in industrial applications long before monolithic materials. This can be attributed to two reasons. Firstly, metals have been used for a long time in the majority of industrial applications as load bearing components, and it was natural to improve their surface properties by the use of diffusion coatings. Diffusion coatings include carbonizing and nitriding, which are probably the most widely used forms of wear resistant coatings. Secondly, although the superior properties of ceramics were recognized quite early, their use in monolithic form was discouraged until very recently because of their brittleness and high manufacturing cost. Nevertheless, ceramic coatings have been accepted for a number of important applications over the last decade for a variety of reasons including economics, material conservation, unique properties and design flexibility which enables separation of bulk and surface properties e.g., coated cutting tools and thermal barrier coatings for jet engines.

The operation of machinery in hostile environments (e.g., high temperatures, high mechanical loads, corrosive environment) often results in performance degradation due to excessive wear and friction, and productivity losses due to shutdowns caused by component failure. Frequently, the component deterioration can be traced to deleterious processes occuring in the surface region of the material. To reduce or eliminate such defects, ceramic coatings have been developed to protect or lubricate a variety of substrate materials, including metals, ceramics and cermets.

The coating approach offers several advantages. One is the ability to optimize independently the properties of the surface region, and those of the base materials for a given application. A second advantage is the ability to maintain close dimensional tolerances of the coated workpiece, since very thin coatings (of the order of a few micrometres) are often sufficient for a given application. Furthermore, cost savings are obtained by using expensive, exotic materials only for thin coatings instead of using bulk components.

Many different processes are in use for the deposition of ceramic coatings and for the modification of surfaces of ceramic coatings and of monolithic ceramics. Table 19 lists some of the more important techniques. The choice of a particular deposition/surface modification process depends upon the desired properties given in Table 20. Additional considerations which can influence the choice of the coating processes include: the purity, physical state and toxicity of the material to be deposited; the deposition rate; the maximum temperature which the substrate can reach; the substrate treatment needed to obtain good adhesion; and the overall cost.

TABLE 19

Processes Used for the Production of Ceramic Coatings
and for the Modification of Ceramic Surfaces

Process category	Process class	Process
Ceramic coating processes:		
Low gas pressure ("vacuum") processes	Chemical vapor deposition (CVD)	Pyrolysis Reduction (plasma assisted) Decomposition (plasma assisted) Polymerization (plasma induced)
	Physical vapor deposition (PVD)	Evaporation (reactive, plasma assisted) Sputtering (reactive, plasma assisted) Plasma-arc (random, steered) Ion beam assisted co-deposition
	Low pressure plasma spraying	Plasma discharge spraying
Processes at elevated gas pressures	Plasma spraying Flame spraying	Plasma arc spraying Combustion flame spraying
Liquid phase epitaxy processes	Wetting process	Dip coating (e.g., Sol-Gel) Brush coating
	Spin-on coatings	Reverse-roller coating
Electrochemical processes	Electrolytic deposition	Cation deposition
	Electrophoretic deposition	Charged colloidal particle deposition
	Anodization	Anion oxidation in electrolytes
	Electrostatic deposition	Charged liquid droplet deposition
Processes for the modification of ceramic surfaces:		
Particle implantation processes	Direct particle implantation	Energetic ion or atom implantation in solids
	Recoil particle implantation	Recoil atom (ion) implantation in solids
Densification and glazing processes	Laser beam densification and glazing	CW-laser power deposition Pulsed-laser power deposition
	Electron beam densification and glazing	Energetic electron beam power deposition
Chemical reaction processes	Gaseous anodization processes	Ion nitriding Ion carburizing Plasma oxidation
	Disproportionation processes	Deposition of molecular species Formed in gas phase
Conversion processes	Thermal diffusion	Diffusion of material from surface into bulk of substrate
Etching processes	Chemical etching	Acidic solutions; lye etching
	Ion etching	Sputter process
Mechanical processes	Grinding Peening Polishing	

SOURCE: Manfred Kaminsky, Surface Treatment Science International, Hinsdale, IL

TABLE 20

Characteristics and Properties of Ceramic Coatings Considered Desirable

Good Adhesion
Precise stoichiometry (negligible contamination)
Very dense (or very porous) structural morphology
Thickness uniformity
High Dimensional Stability
High Strength
High fracture toughness
Internal stresses at acceptable levels
Controlled density of structural defects
Low specific density
High thermal shock resistance
High thermal insulating resistance
High thermal stability
Low (or high) coefficient of friction
High resistance to wear and creep
High resistance to oxidation and corrosion
Adequate surface topography

Source: Manfred Kaminsky, Surface Treatment Science International, Hinsdale, IL

The key features of structural ceramics and ceramic coatings are given below:

Factor	Monolithic Ceramics	Ceramic Coatings
Corrosion resistance	+	+
Wear resiatance	+	+
Hot strength	+	0
Thermal shock resistance	+	0
Thermal insulation	+	+
Design alteration	-	+
Failure mode	-	0
Manufacturing process	-	+

+ = very attractive feature
0 = attractive feature
- = drawback

Theoretically, ceramic coatings can be deposited on any substrate material. This versatility has tremendous implications in materials designing since it allows the use of many materials which were previously considered unsuitable for demanding applications. Metals and plastics can now be insulated with ceramic coatings to minimize loss of mechanical properties at elevated temperatures, as well as corrosion properties experienced by metals. The various ceramic coatings and films that are now routinely deposited on a wide array of substrate materials are listed in Table 21.

The deposition techniques of ceramic coatings are numerous and are dependent on application requirements and cost considerations. The resultant microstructure and performance vary dramatically among coatings deposited by different methods. The four processes most frequently used commercially are:

. Wet processes

. Thermal spraying

. Chemical Vapour Deposition (CVD)

. Physical Vapour Deposition (PVD)

In general, the wet processes and thermal spraying are more applicable for oxide coatings while CVD and PVD are preferred for non-oxide coatings. Recent developments in coating deposition techniques for achieving improvement in tribological performance, corrosion

TABLE 21

Selected Substrate and Coating Materials

SUBSTRATE	Al_2O_3	ZrO_2	TiC	B_4C	SiC	TiN
Steel	X	X	X	-	-	X
Superalloy	-	X	-	-	-	X
Titanium Alloys	-	-	X	-	-	X
Graphite	X	-	X	X	X	X
Silicon Carbide	X	-	-	-	-	X
Silicon Nitride	-	-	-	X	X	-
Carbon/Carbon	-	-	-	X	X	X
Nylon	X	X	-	-	-	-
Polyester	X	X	-	-	-	-
Polyimides	X	X	-	-	-	-

resistance and oxidation resistance are listed below:

Properties	Wet Process	Thermal spray	CVD	PVD
Tribological performance	-	X	X	X
Corrosion resistance	X	X	X	X
Thermal insulation	-	X	-	-
Oxidation Resistance	X	X	X	-
Optical properties	-	-	X	X
Decorative function	-	-	X	X

The applications for CVD and plasma coatings are listed in Tables 22 and 23, respectively.

The sizable market for ceramic coatings appeals to many companies contemplating to enter the advanced ceramics business. C.H.Kline & Co* estimate the world market for ceramic coatings in structural applications to be about US$ 1.1 billion in 1985 and project that this figure will triple by the year 1995. Currently, the U.S. and Western Europe account for about 85% of the demand for ceramic coatings. Shown in Figure 12 are the relative shares of the ceramic coatings market for various end uses. Around 45% of the market is in the form of optical coatings for construction applications and the remainder of the market is represented by coatings for structural parts. These are primarily used on cutting tools, military products, and chemical processing equipment. The report projects that since the technologies and markets for ceramic coatings are already more developed than for other structural ceramics, ceramic coatings will find use in automobile and turbine engines well before monolithic structural ceramics and composites as shown in Figure 13. The forecast is that ceramic coatings will be introduced in automotive engines by 1995 because of their advantages with regard to manufacturing costs, non-catastrophic failure characteristics, and minimal changes in physical design. The expected applications include coatings on cylinder liners, cylinder heads, and piston caps. A 25% annual growth rate is forecast. Other high growth applications cited for ceramic coatings include metal fabrication equipment and wear and corrosion resistant parts for chemical processing.

---

* "World Markets for Ceramic Coatings". Charles H.Kline & Co. Industrial Ceramics, Volume 7, No.3, p 169. (1987).

TABLE 22

Wear Resistant CVD Coatings and Their Applications

Coating	Applications
Titanium Carbide	Sintered carbide cutting tips, steel pressed tools, punches and dies, and wear parts.
Titanium Nitride	As above. Also, release coatings and decorative coatings
Titanium Diboride	Coal gasification, coal-oil conversion components, cutting tools, wear coatings for aircraft engines(experimental).
Chromium Carbide	Slide wear parts
Zirconium Carbide	Experimental application to sintered tips.
Hafnium Carbide	Experimental application to sintered carbide tips.
Aluminum Oxide	Sintered carbide cutting tips in various combinations with TiC/TiN.
Boron Diffusion	Erosion resistance on mining tools and dust/grit handling systems.
Nitrogen Diffusion	Numerous types of steel wear parts (e.g., plastics extrusion screws)
Carbon Diffusion	Small steel components (e.g., fasteners, switch actuator mechanisms).

TABLE 23

Typical Applications for Plasma Sprayed Ceramic Coatings

Sector	Workpieces	Spraying materials	Properties
Aerospace	Turbine blades, cumbustion chambers, afterburners	Zirconia	Heat insulation, Heat resistance
	Rocket nozzles	Tungsten	High temperature erosion resistance
Automotive	Piston rings, shift forks	Molybdenum	Abrasion resistance, Scoring resistance
	Cylinder liners	Ferrous alloy	Sliding wear resistance
	Rocker arms, cam shafts	Molybdenum composite	Abrasion resistance Scoring resistance
Engines	Gas turbine blades	Zirconia	Heat insulation, Heat resistance
	Diesel engine pistons, valves	Zirconia	Heat insulation, Heat resistance
	Axles, bearings	Chromium carbide	Abrasion resistance
Electrical equipment	Magnetic recording heads	Titania	Abrasion resistance
	Hotplates	Gray alumina	Abrasion resistance
	Electrical insulation substrates	White alumina	High temperature electrical insulation
	Far-infrared heaters	Zirconia	
Steelmaking equipment	Furnace rolls, hearth rolls	Zirconia	Heat resistance
	Guide rolls	Chromium carbide	Abrasion resistance
	Blast furnace tuyeres	Zirconia	Heat resistance
Plant equipment	Plungers, sleeves, mechanical seals		Abrasion resistance, Corrosion resistance
	Burner impellers, protective tubes for thermometers	Nickel alloy	High temperature corrosion resistance
	Agitator blades	Nickel alloy	Abrasion resistance, Corrosion resistance
	Textile machine guides, bobbins	Alumina, titania	Abrasion resistance, Corrosion resistance
Machine tools	Lathe beds	Self-melting alloy	Abrasion resistance, Sliding wear resistance
	Gauges	Carbide	Abrasion resistance
Materials	Plastic-ceramic composites	Alumina, etc.	
	Ceramic-metal composite		

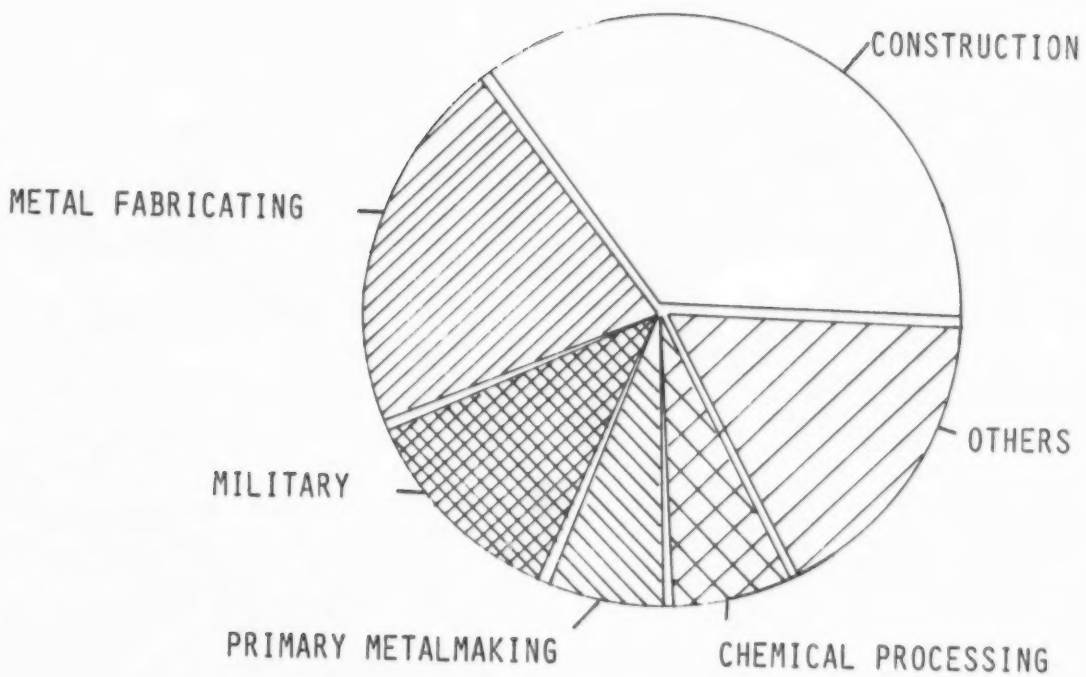


Figure 12. World Markets for Ceramic Coatings by end use Industries in 1985

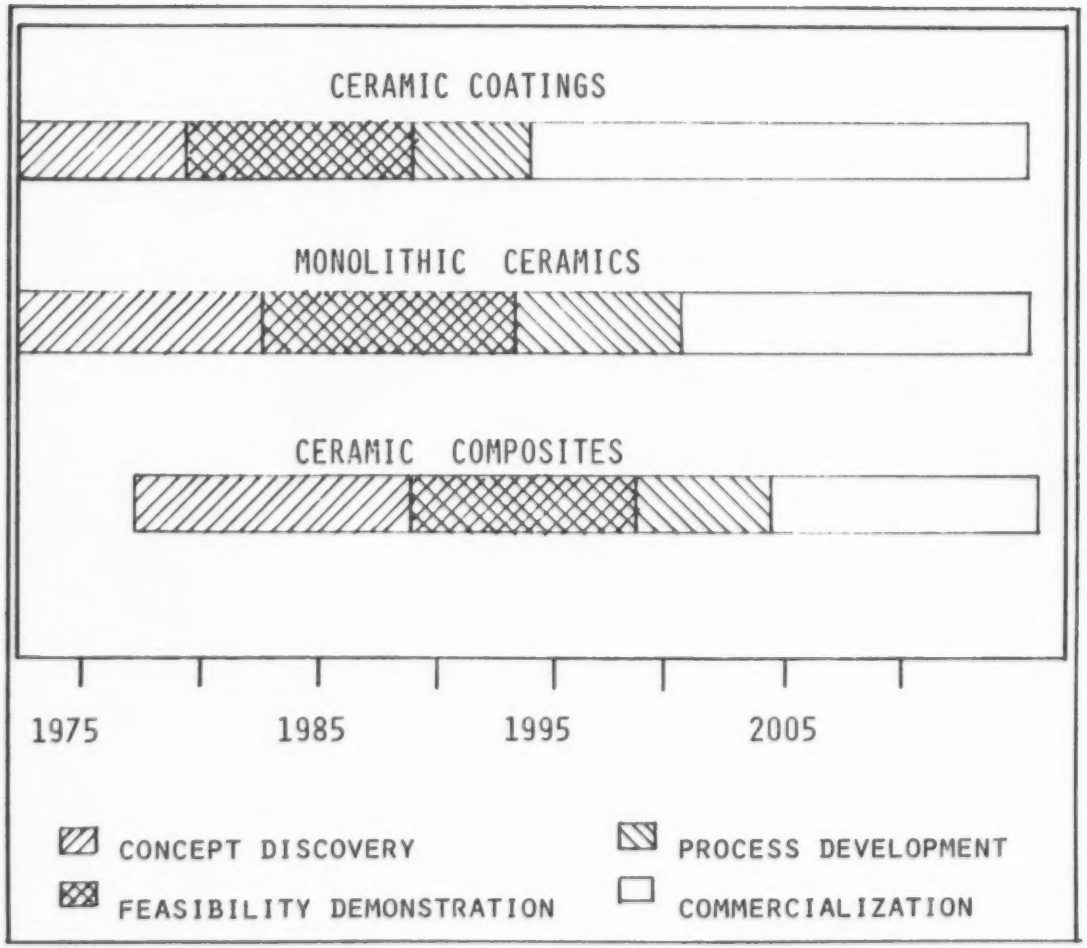


Figure 13. Commercial Status of Various Forms of Advanced Ceramics for Engines for the Years 1975-2010

Similar projections have been made by Chan and Wachtman**. Due to their flexibility and relatively low manufacturing costs, ceramic coatings are expected to enjoy exceptional growth. The world market is projected to triple to over US$ 3 billion by the year 1995 i.e., an average groth rate of about 13% per year. The industrial segments propelling this growth, as shown in Figure 14, include components for engines (28%), marine equipment (18%), and chemical processing equipment (15%). Military, construction glass, consumer products, petrochemical equipment, primary metal making and metal fabricating activities are also expected to contribute to the anticipated growth.

The ceramic coating industry is very fragmented. Since the business is very application specific, and the necessary expertise is normally acquired slowly, companies involved in this business usually engage in a limited range of activities. Only a few large firms like Union Carbide and Metco in the U.S. are now fully integrated. However, the apparent benefits and ecomomic implications of ceramic coatings has encouraged many U.S. companies to pursue the business through technology licencing, joint ventures and acquisition. Foreign companies are also active e.g., Nippon Steel of Japan has purchased Electroplasma in the U.S.; Sulzer Brothers in Switzerland acquired Plasma-Technik AG in W.Germany and Alloy Metals in the U.S.

Considerable industrial plasma activities exist in Canada and will be discussed in a subsequent section.

** "Expanding World of Ceramic Coatings". K.K. Chan and J.B. Wachtman. Ceramic Industry. pp 24-26, September 1987.

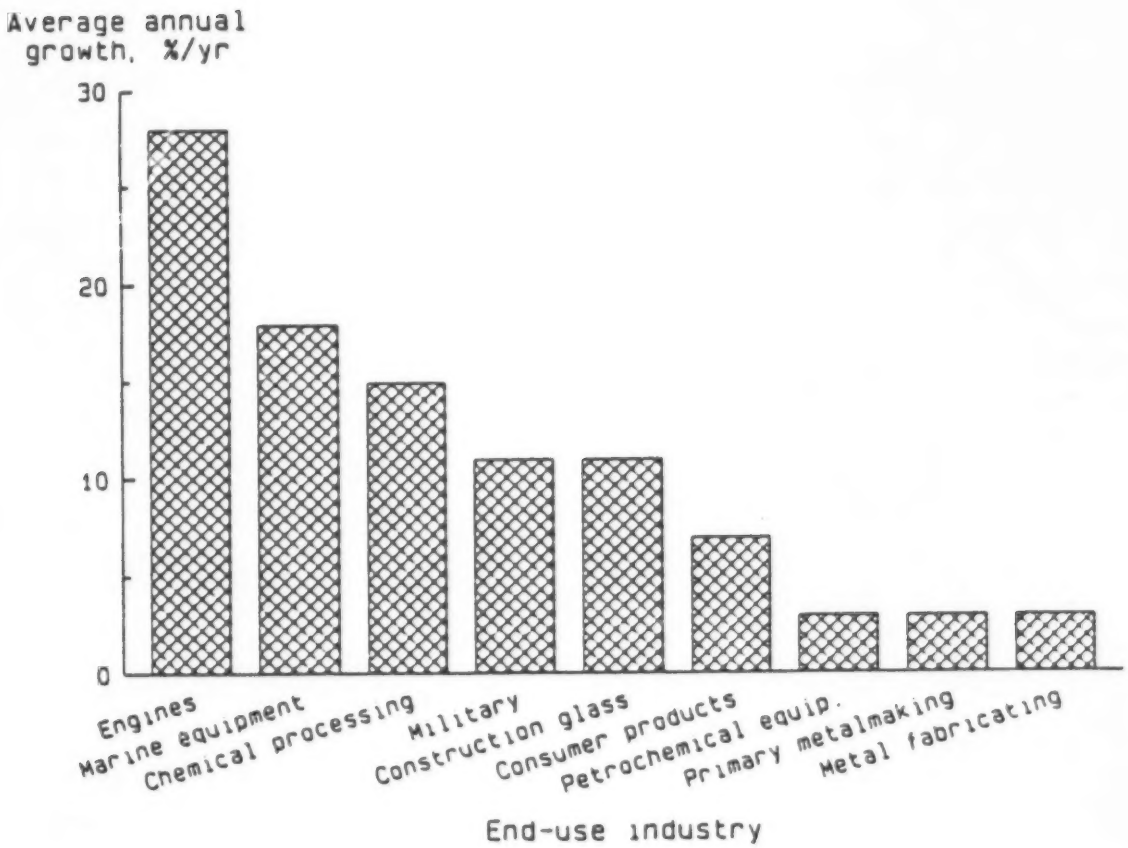


Figure 14. Projected Growth Rate for Ceramic Coatings by end use Industry, 1986 - 1995

4.5 Status of Advanced Functional Ceramics

4.5.1 General

As discussed before, the three important groups of ceramic materials under this category are: (i)electronic ceramics, (ii) chemical and biological ceramics, and (iii) nuclear cermics. To date, from a commercial point of view, the most important category is electronics ceramics. However, the chemical and biological applications are becoming important and are expected to grow substantially in the coming decades. Although nuclear ceramics are important, their growth is not expected to be high because of their restricted market.

4.5.2 Bioceramics and Ceramic Implants

The interest in ceramics for implants began in in the 1960's as a means to alleviate or eliminate the two problems encountered with metal and polymer implants: loosening of the implants leading to breakage of either the implant, bone or both; and the body's sensitivity to foreign materials resulting in the development of non-adherent fibrous capsule around the implant. Research on bioceramics has spawned not only important new biometerials used in clinical prostheses but also the scientic discovery that implants can be made that are not rejected by the body. During the last 25 years dozens of ceramic compositions have been tested to determine their potential use in implants. However, relatively few have withstood the rigorous dual requirements of safety and efficacy for use as functional prostheses.

Notwithstanding failures and problems R&D on bioceramics is being being pursued vigorously, particularly in Japan, the impetus being the huge market potential listed in Table 24.

4.5.3 Electronic Ceramics

Ceramics have been used in electronics from the beginning, both as inert (substrates, packaging) and as active components (resistors and capacitors). Starting in the early 1970's, electronic ceramics have become more important to meet the needs of the electronics industry, particularly miniaturization leading to microelectronics. To day, Japan is the world leader in the manufacture of electronic ceramics and has captured about 50 per cent of the world market.

The electronic ceramics market can be divided into six equal parts (Figure 15) comprising of: resistors and sensors; piezoelectric materials; hard and soft ferrites; multilayer capacitors; substrates and insulators; and optical fibers, discs and display.

The nature of the electronic ceramics market is changing dramatically to accommodate technological changes and product

TABLE 24

Biomaterial Market Potental

Application	1986 Number	1986 Cost	1986 Market (millions)	1996 Number	1996 Cost	1996 Market (millions)
Total hip	300 000	$ 600	$ 180	400 000	$ 700	$ 280
Total knee	150 000	400	60	200 000	500	100
Ankles/elbows/shoulder	50 000	500	25	700 000	600	420
Finger	400 000	50	20	600 000	100	60
Fixation pins/plates	1 000 000	50	50	1 200 000	60	72
Tooth implants	300 000	500	150	1 500 000	250	375
Periodontal treatment	200 000	20	4	1 000 000	50	50
Ridge augmentation	100 000	20	2	2 000 000	40	80
Ridge maintenance	250 000	10	2.5	15 000 000	20	300
Mammary prostheses	400 000	100	40	500 000	120	60
Intraocular lenses	1 000 000	400	400	1 500 000	750	1 125
Middle ear prostheses	30 000	150	4.5	35 000	200	7
Cochlear prostheses	500	10 000	5	10 000	10 000	100
Sutures	17 500 000	2	35	18 000 000	2	36
Facial augmentation	6000	200	1.2	10 000	250	5
Myringotomy tubes	300 000	30	9	500 000	50	25
Pacemakers	190 000	1500	285	200 000	2000	400
Heart valves	40 000	2000	80	60 000	2500	150
Arterial prostheses	250 000	200	50	500 000	250	125
Ventricular assist	100	7500	.75	500	10 000	5
Vascular bypass	500 000	?	?	1 000 000	?	?
Totals: U.S.			$1403.95			$3775
Worldwide			$3509.87			$9437

(Advanced Ceramic Materials, Vol 1, No 4, 1986)

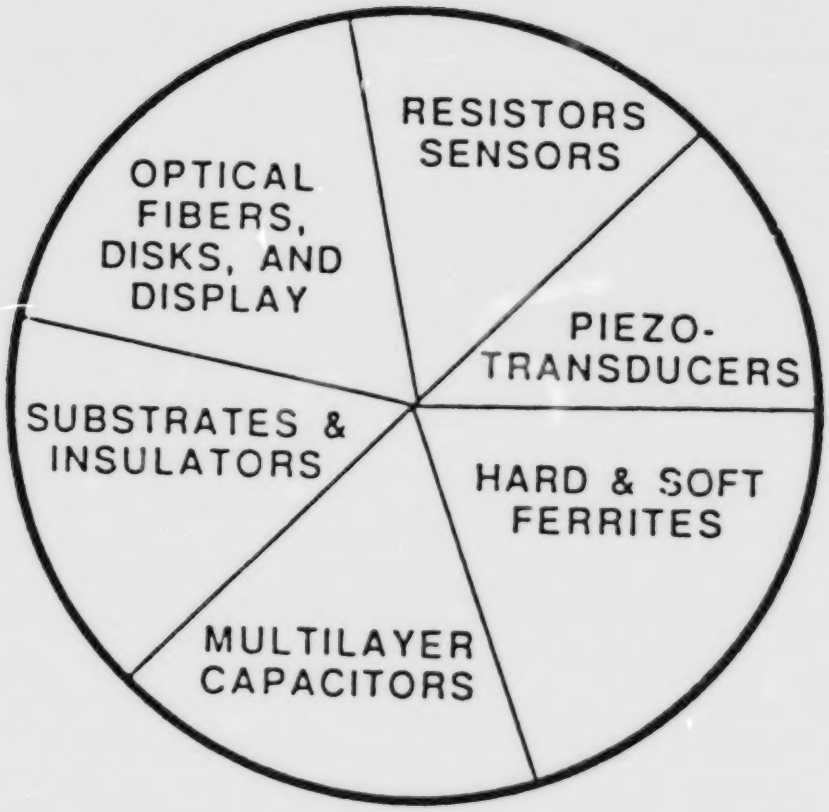


Figure 15. Electroceramics Market

[after Robert E. Newnham, Adv. Cer.Matls. Vol 3, No 1, 1987]

requirements in the electronics industry. Firstly, the old system of individual components assembled into a system for particular application has given way to microelectronics. In microelectronic circuitry all the active and passive components are integrated i.e., ceramic resistors and capacitors are not discrete components but are incorporated on an alumina substrate. Ceramic packaging for high quality microelectonics is also in place. The need for very high speed communication within the device to meet the needs of high speed computers and data processing systems is pushing the multilayer technology.

As in all rapidly evolving fields of science and engineering, there is a sense of excitement as a number of different technologies come together in a synergistic manner. Miniaturization and integration are technological goals in virtually all electronic circuitry. Different kinds of circuitry that are being studied/developed are shown in Figure 16. To meet these needs, the "golden age of electroceramics" is beginning to take shape(*).

An overview of electroceramics is given in Figure 17, which illustrates the various atomistic mechanisms utilized in ceramic circuit components. Multilayer capacitors, piezoelectric transducers, and PTC thermistors make use of the properties of ferroelectric pervoskites with their high-dielectric permittivity, large piezoelectric coefficients, and anomalous electrical conductivity. Several kinds of mechanisms are operative in thermistors and other ceramics used as sensors; most are based on electrical resistivity, but the causes are different.

The age of integrated ceramics is taking shape. Unitl recently multilayer ceramic packages of dielectric strata with metallic circuitry printed on each layer and interconnected through metallized via holes between layers. Now additional circuit elements are being added. In the last two years buried capacitors and resistors have been added to the three-dimensional packages, and other components are expected to follow shortly. Future developments in the field of integrated ceramics are illustrated in Figure 18.

The four technological areas which are growing rapidly and, therefore, offer opportunities for new businesses are:

. Multilayer circuits, particularly capacitors
. Sensors
. Integrated optics
. Superconductors.

(*) "Golden Age of Electroceramics". Robert E. Newnham. Adv.Cer.Matls. Volume 3, No 1, (1987).

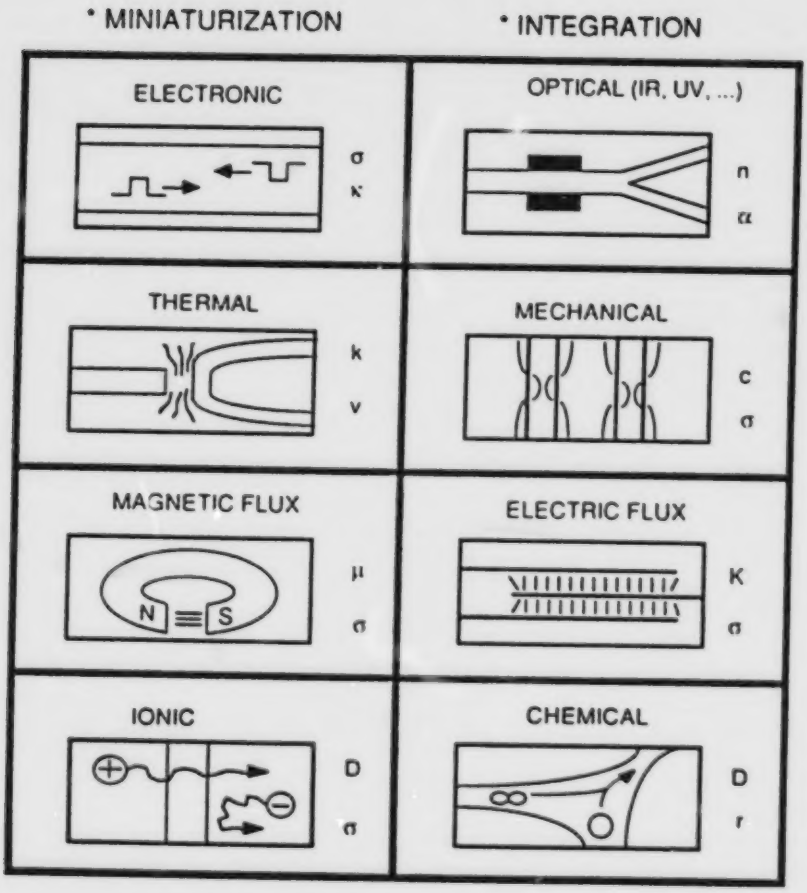


Figure 16. Circuitry in Ceramic Materials for Use in Electronic Packages, Integrated Optics, Cooling Systems, Electromechanical Transducers, Magnetic Recording, Multilayer Actuators, Ionic Batteries, and Chemical Sensors.

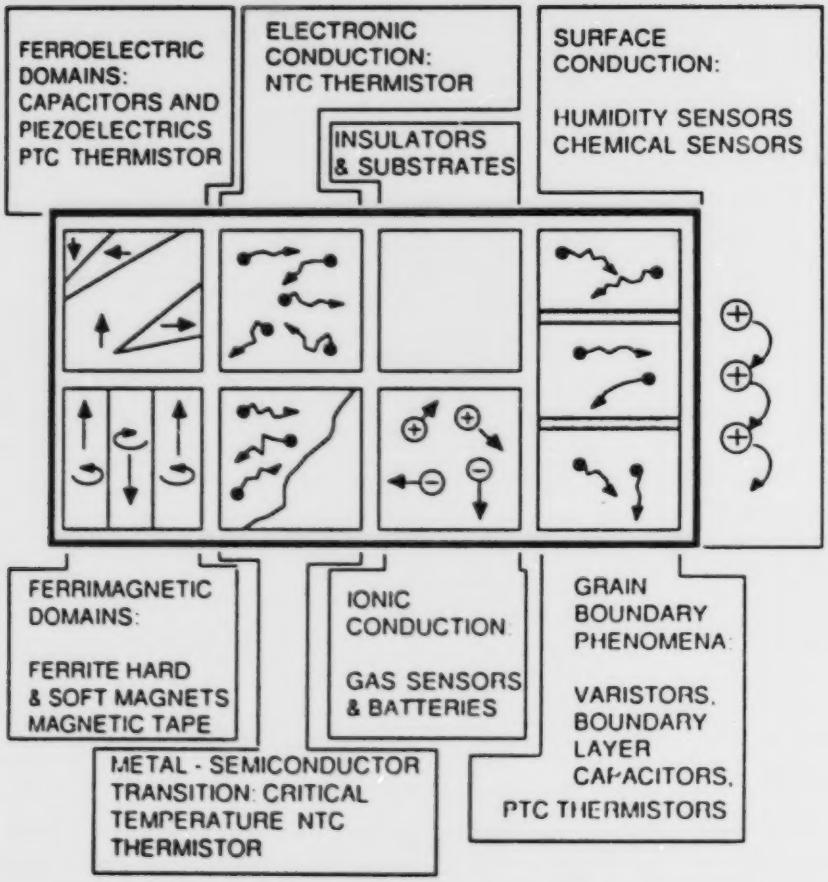
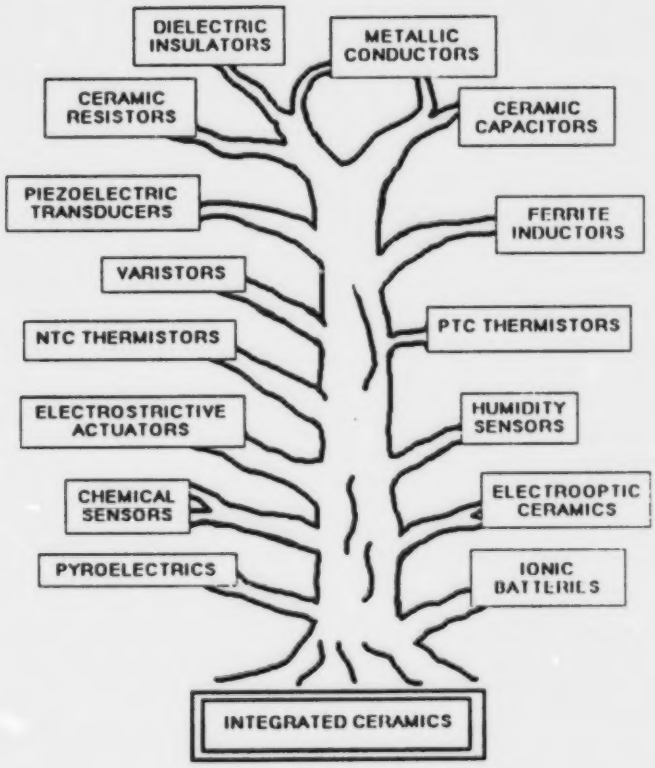

FERROELECTRIC DOMAINS: CAPACITORS AND PIEZOELECTRICS PTC THERMISTOR
ELECTRONIC CONDUCTION: NTC THERMISTOR
INSULATORS & SUBSTRATES
SURFACE CONDUCTION:
HUMIDITY SENSORS CHEMICAL SENSORS
FERRIMAGNETIC DOMAINS:
FERRITE HARD & SOFT MAGNETS MAGNETIC TAPE
IONIC CONDUCTION:
GAS SENSORS & BATTERIES
GRAIN BOUNDARY PHENOMENA:
VARISTORS, BOUNDARY LAYER CAPACITORS, PTC THERMISTORS
METAL - SEMICONDUCTOR TRANSITION: CRITICAL TEMPERATURE NTC THERMISTOR

Figure 17. Ionic and Electronic Mechanisms Involved in Electroceramic Components.



Future 18. Integrated Ceramic Packages of the Future Incorporating Many Different Components.

4.5.3.1 Multilayer Circuits

Multilayer circuits (MLC) are expected to advance at the expense of single-layer ceramics as the demand increases. It has been projected that the growth in multilayer technology will follow three directions. Firstly, lowering production costs; secondly, changes in technology to bring about the required increase in reliability; and, thirdly development of new materials technologies to meet the needs of future generations of integrated circuits. The latter is considered important because competition for future market share will drive technology of MLCs towrds compatability with future generations of integrated circuits which are expected to be faster and denser than the current generation.

Capacitors are electronic components used to store electrical charges and are employed in conjunction with active electronic components such as semiconductors. Ceramic materials are used in capacitors as dielectric layer i.e., to insulate the electrodes and to store electrical charge. Manufacture of discrete capacitors is a mature industry and the present demands are met by established manufacturers. Multilayer ceramic capacitors, however, are relatively new and form the largest and fastest-growing class of capacitors amounting to about 3.3 billion units with a market value of US$ 340 million in 1981 in the U.S. A growth of about 20% is expected throughout the 1980's. Japan is also a leader in this technology and in manufacturing. The market for MLCs is expected to increase from 110 million pieces (Yen 420 million) in 1985 to 443 million pieces (Yen 1,780,000 million) in 1995.

4.5.3.2 Sensors

A sensor is a device that responds to a stimulus. Sensors of various sorts have been in use for many years. Early examples of sensors include compasses, thermometers, and barometers. Recently, there has been increasing interest in the field of sensors, and the sensor industries appear ready for a period of rapid growth. The reasons for this include both market and technology factors.

On the demand or market side, the availability of inexpensive microprocessors and the develoment of robotics open up many possibilities for automation in industry and in the home. Automation is expected to bring a a large increase in the number of sensing points. However, widespread application of automation requires inexpensive, reliable methods for real-time data acquisition or monitoring i.e., sensors. In order to implement automation, sensors will be required to measure a large number of physical and chemical phenomena. Six general categories of sensor stimulii have been identified:

- Physico/mechanical
- Electrical
- Magnetic
- Thermal
- Radiation
- Chemical

On the technology side, considerable basic research that has been done on a number of materials allows an understanding of a variety of sensing mechanisms. As a result practical, inexpensive, accurate and reliable sensing devices are available for monitoring a wide variety of physical and chemical phenomena. Continued work in these areas will allow both improvements in existing classes of sensors and development of new sensing devices.

A number of advanced ceramic materials have special properties which give them sensing capabilities. There are now ceramic-based devices that respond to a variety of stimuli. Typically, the electrical properties of the ceramic change in response to the presence or level of the phenomena being detected. The various types of ceramic-based sensors, along with the ceramic materials used in each, are listed in Table 25. The application areas, ceramic materials used, operating principles, market size, and technological maturity and barriers will be briefly presented.

Piezoelectric Sensors

Piezoelectric devices represent the largest existing market for ceramic sensors at present; the world sales (1980) has been estimated at US$ 325 million. Piezoelectrics are used to convert mechanical energy into electric energy or vice versa in a variety of applications including ignitors, photoflash actuators, resonators, beepers, paging devices, and ultrasonic devices.

The active ceramic components in piezoelectrics have been based on lead-zirconate-titanate with various additives since the 1960's. The specific composition choice gives rise to electromechanical coupling coefficients which are also related to the orientation of ferroelectric domains and the dielectric constant. Ceramic piezoelectric devices have been in use for about 30 years, and the materials technology is relatively well developed and understood. New PZT-polymer transducers with much greater sensitivity are being actively developed.

Negative Temperature Coefficient (NTC) Thermistors

NTC thermistors represent another mature technology with a relatively large existing commercial application of ceramic sensors (approximately US$ 75 million per year world sales). The name of this type of sensor derives from the fact that the coefficient of

TABLE 25

Types of Ceramic Sensors

SENSOR CATEGORY	TYPICAL CERAMIC MATERIAL
Piezoelectric Devices	Lead-zirconate-titanate
Negative Temperature Coefficient Thermistors	Complex systems of nickel, manganese, cobalt, and copper oxides
Positive Temperature Coefficient Resistors	Combinations of barium titanate with either strontium or lead titanate
Varistors	Zinc Oxide
Oxygen Sensors	Zirconia stabilized with yttria or magnesia
Humidity sensors	Magnesia-chrome-tirania, or alumina
Combustible and Toxic Gas Sensors	Various semiconducting oxides including tin, zinc, and iron oxides

resistivity varies inversely with temperature. NTC thermistors are used in a number of applications including the control of non-linear circuits, temperature mesurement, various automobile applications and medical thermometry.

The active ceramic components of these sensors are based largely on spinel solid solutions in complex systems of the oxides of nickel, manganese, cobalt, and copper. Like piezoelectric devices, NTC thermistors have been available commercially for about 30 years and represent a relatively mature technology.

Positive Temperature Coefficient (PTC) Resistors

PTC resistors derive their name from the fact that their electrical resistivity varies positively with temperature. They are used in a wide variety of applications including self-regulating heating devices, current limiters, and sensors for temperature, air flow, and liquid level.

PTC resistors are based on combinations of barium titanate and either strontium or lead titanate. The non-linear electrtical properties of PTC resistors are derived mainly from electrical junctions at grain boundaries. Among the key technological needs remaining is the development of a better understanding of conducting behaviour at the grain boundaries.

Varistors

Varistors are voltage-dependent resistors possessing non-linear electrical properties due to the existence of electrical junctions at grain boundaries. They are used to protect semiconductor-based electronic equipment from voltage surges. Principal applications include use in TV receivers, industrial electronic equipment, microwave ovens, and automotive electronics.

Since the late 1960's varistors have been based on zinc oxide. Prior to that time silicon carbide was used exclusively.

Oxygen Sensors

Oxygen sensors are used to detect the presence of and quantify the amount of oxygen present in an atmosphere. Their current principal application is in automoble exhaust metering where they have been used since 1977. An important new application is in process contol for steel making. Oxygen sensors are also used in a variety of applications including combustion control operations, gas manufacture, and food and beverage packaging.

The oxygen sensor is based on stablized or partially stabilized zirconia. In automobile applications, the stabilizing agent is yttria; in steel making magnesia stabilized zirconia is used.

Humidity Sensors

Humidity sensors are used in a number of applications including microwave ovens, air conditioners, and various industrial operations. Ceramic humidity sensors have been commercially available for some time, however, it is only since 1978 that low-cost stable sensors were made available for microwave oven applications. Production has achieved a significant volume.

Alumina had been used as the basis of humidty sensors prior to the late 1970's. The newer sensors developed for microwave oven applications are based on sensing elements composed of a magnesia-chrome-titania ($MgCr_2O_4$-TiO_2) spinel solid solution. The resistance of the latter type of sensor is related to the relative humidity of the environment through chemical adsorption and dissociation of water. Key technological barriers include aging in high-humidity environments and a lack of understanding of gas-surface interactions.

Combustible and Toxic Gas Sensors

Ceramic sensors for the detection of combustible gases were developed in the 1960's in Japan and ceramic sensors for toxic gases were developed in early 1970's in the U.S. These sensors are based on porous semiconducting oxides such as tin, lead, and zinc oxides. The electrical conductivity of these materials responds to the presence and concentration of various gases.

Two important components of a gas sensor's performance are its "sensitivity" (ability to respond to gases in low concentration) and "selectivity" (ability to respond to a particular gas, or a set of gases in the presence of others). The sensitivity of sensor depends upon a number of factors including the properties of the specific material. Sensitivity, in addition to composition, also depends upon the surface properties of the material.

In practice, there are several structural routes to producing highly sensitive gas ceramic sensors, including partial sintering of fine powders and thin film technology. The major Japanese producers appear to favour the powder route wheras leading U.S. producers are believed to use thin film approach.

Gas sensors have a large number of present and future uses. The important uses are:

- Environment monitor and control
- Industrial process control
- Energy management

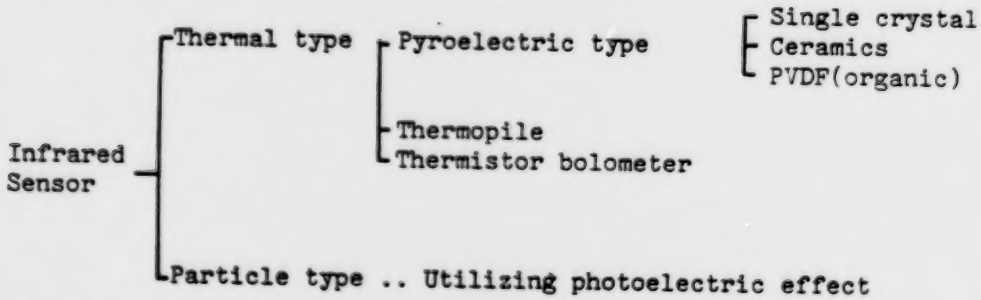
Toxic and combustible gas-monitoring is used in a variety of industries including oil and gas drilling and refining, power generation. and the chemical and petrochemical industries.

Accurate sales data are not available. However, Charles River Associates estimates the world sales to be about US$ 25-30 million in 1983. The Japanese sales account for US$ 15-20 million. The growth rate in Japan is said to be 40-60 per cent per year. The world sales by 1990 are estimated to be about US$ 90-160 millions for existing uses and US$ 260-430 millions, if projected applications such as furnace monitoring, carbon monoxide monitoring, automobile exhaust monitoring etc., become successful.

Potential entrants into this industy may eventually play a major role in the development of the technology and may capture a large fraction of sales. Many major corporations in both the U.S. and in Japan are said to have active R&D programs. The U.S. firms in this category are said to include General Motors, Ford, Bendix, General Electric, and Motorola. Major Japanese firms in this area include Matsuhita, Toshiba, Nissan and Hitachi.

Infrared Sensors

Infrared sensors are becoming very important for consumer applications, mostly for security equipment. Although commercial utilization is only a decade old, the market is growing rapidly. The types of infrared sensors are shown below:



The major pyroelectric materials and manufacturers in Japan are listed in Table 26. Presently, only PZT ceramics are used in Japan, however, single crystal materials (lithium niobate, lithium tantalate, strontium-barium-niobate) are expected to find increased use as availability and cost factors improve. The market size for infrared sensors in Japan is given in Table 27.

TABLE 26

List of Pyroelectric Materials and Japanese Manufacturers

Material	Curie Temp. Tc(°C)	Specific Inductive Capacity	Coefficient of Pyroelectricity ($C.cm^{-2}.K^{-3}$)	Specific Heat at Constant Volume $c'(q.cm^{-3}.K)$	$\lambda/\varepsilon \cdot c'$ (C.cm.J)
TGS (Inorganic)	49	35	4.0×10^{-8}	2.5	4.6×10^{-10}
$LiTaO_3$ (Single crystal)	618	43 54	1.8 2.3×10^{-8}	3.2	1.3 1.35×10^{-10}
PZT (Ceramics)	200 270	380 1800	1.8 2.0×10^{-8}	3.0	0.2 0.4×10^{-10}
Deformed PZT (Ceramics)	220	380	17.9×10^{-8}	3.1	1.5×10^{-10}
$LiNbO_3$ (Single crystal)	1200	30	0.4 0.5×10^{-8}	2.8	0.4 0.6×10^{-10}
$PbTiO_3$ (Ceramics)	470	200	6.0×10^{-8}	3.2	0.94×10^{-10}
SBN (Single crystal)	115	380	6.5×10^{-8}	2.1	0.8×10^{-10}
PVDF (Organic Macromolecular)	120	11	0.24 0.4×10^{-8}	0.33	0.9 1.5×10^{-10}

Note: TGS: $(NH_2\text{-}CH_2\text{-}COOH)_3H_2SO_2$, Glycine Sulfate
PZT: $(PbxZryTiz)O_3$
Deformed PZT: $[Pb(SnSb)O_3\text{-}PbTiO_3\text{-}PbZrO_3]$
SBN: [Srx Bay Nb_2O_6] normally x=0.48, y=0.52
PVDF: Crystalline macro molecule of polyvinyl fluoride $[(CH_2\text{-}CF_2n]$ or PVF_2

Pyroelectric Type Infrared Sensor

Type	Domestic Production	Import
Single crystal ($LiTaO_3$)	Sanyo Electric Co., Ltd. Matsushita Denshi Buhin (Matsushita Giken)	Plessey Eltic
Ceramics (PZT)	Murata Mfg. Nihon Ceramic Horiba, Ltd.	Plessey Mullard
Organic (PVDF)	Matsushita Electric Insdustrial Co., Ltd. Matsushita Communication Industrial Co., Ltd.	

TABLE 27

Projected Market Size for Infrared Sensors in Japan

1) Volume

(Unit: 1,000 pcs)

Type \ Year	1983	1984	1985 (prospect)	1984 Ratio
Infrared sensor	4,536	5,720	7,104	100
Thermal type sensor	4,296	5,420	6,744	94.8
Pyroelectric sensor	4,200	5,300	6,600	(92.7)
Others	96	120	144	(2.1)
Grain type sensor	240	300	360	5.2

2) Value

(Unit: 100 yen)

Type \ Year	1983	1984	1985 (prospect)	1984 Ratio
Infrared sensor	28	34	40	100
Thermal type sensor	25	30	36	88.2
Pyroelectric sensor	24	29	35	(85.3)
Others	1	1	1	(2.9)
Grain type sensor	3	4	4	11.8

Pyroelectric sensors are also divided into three groups: single crystal, polycrystalline ceramic and PVDF. The applications for pyroelectric devices are listed in Table 28. The demand for pyroelectric sensors has grown at a rate of about 25% per year in Japan since 1983 and is expected to continue at this rate for the rest of this decade.

4.5.3.3 Integrated Optics

Integrated optic circuits are optical guided-wave devices that perform a variety of processing functions on the light beams that they guide. A typical processor is shown in Figure 19. The largest end use for these products will be in fiber optic communication systems, including commercial telecommunications, military communications, and computer-to-computer data communication links. Other potential uses include: optical sensing, optical signal processing, and optical computing. In the near term, the integrated optic devices are expected to be manufactured using single-crystal ceramic materials such as lithium niobates as substrates because of their desirable electro-optic properties and ease of fabrication. In the long run, semiconductor materials such as gallium arsenide may also be used as substrate.

Ceramic materials are currently considered the "materials of choice" for two reasons. Firstly, ceramics exhibit stronger electro-optic effects than semiconducting materials. This implies that more compact devices requiring smaller voltages can be fabricated. Secondly, device fabrication is currently easier and cheaper for ceramics.

Virtually all the activity in integrated optics is in the research and development stage. In the USA the biggest activity is in A.T & T. Other companies include: Hughes, TRW, Westinghouse, McDonnell Douglas, and Crystal Technology. A number of companies in Japan including Toshiba are said to be active in this area.

It has been estimated that the total economy-wide savings due to the use of integrated optic devices in communications applications will exceed US$ 1 billion by the year 2000. Hence, the interest and activity in this area.

4.5.3.3 Ceramic Superconductors

The phenomenon of superconductivity i.e., the ability to loose electrical resistance at certain temperatures, was first discovered in the metal mercury in 1911 by H.K. Onnes, for which he was awarded a Nobel Prize. Onnes observed that mercurey looses its electrical resistance and becomes conducting at 4 ^{o}K (0 degrees Kelvin = -273 ^{o}C). The superconducting temperature is denoted by the term T_c. Although the importance and industrial significance was recognized quite early, and attempts were made to increase the superconducting temperature to

TABLE 28

Applications of Pyroelectric Devices

Security

Area of Application	Actual Cases
Disaster prevention	Early detection of fire Safety maintenance of oil tank Monitoring of air and gas in building equipment
Crime prevention	Invasion alarm Body counter
Search and rescue	Search for victims after fire Search and rescue of victims on sea, in snow, etc.
Environment control	Waste water from plant Hot water draining control Waste oil control

Energy Saving

Area of Application	Actual Cases
Electronic power supply	Effective temperature control of microwave oven, oilstove and other heating equipment Temperture sensor for energy saving design of air conditioner and refrigerator Temperature measuring instruments for motor, power transformer and electronic component
Nuclear Power	Hot waste water control in nuclear power plant Detection of abnormal temperature
Plastic Rubber	Plastic moulding process control such as temperature measurement of moulding resin and die
Automobile	Measurement of automobile exhaust gas Temperature measurement of engine and radiator
Food	Temperature control Packaging process control
Civil Engineering and Construction Agriculture and Atmospheric Condition	Temperature control of freezer Analysis of temperature and gas in greenhouse environment for cultivation
Petroleum and Chemicals	Temperature control of explosive and/or inflammable materials Reaction temperature measurement
Medical Science and Health Care	Measurement of temperature distribution on human body Measurement of human body motion
Metal and Metallurgy Iron and Steel	Temperature monitoring Measurement of temperature distribution Measurement of board thickness Mesurement of rod count
Machinery and Processing	Temperature measurement of burning gas Temperature measurement of materials in cutting process Temperature control of oil hydraulic machine

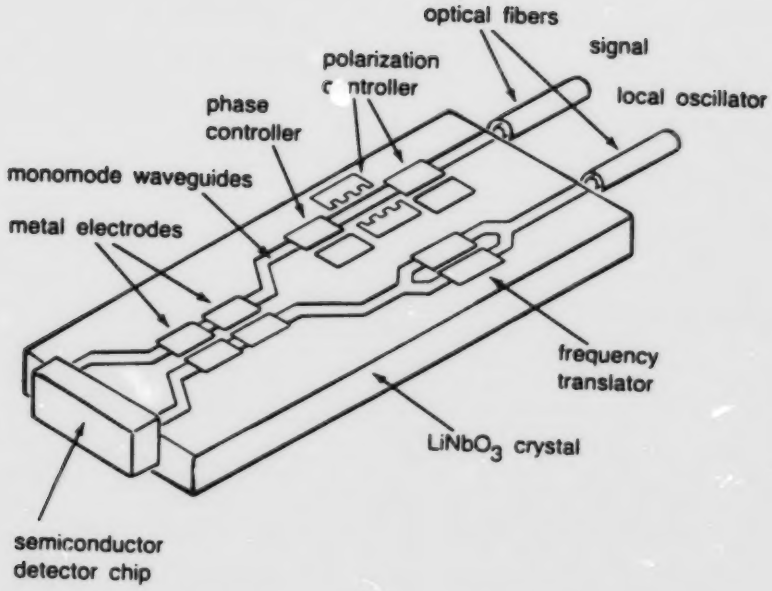


Figure 19. Typical Integrated Optic Processor based on Lithium Niobate Substrate

higher values, progress was slow and limited as shown in Figure 20.

Until very recently, the phenomenon was known to exist only in metals - niobium or niobium metals- at temperatures below 23.3 ^{o}K which can be maintained only by using costly liquid hydrogen or helium.

The recent discovery of Bednorz and Muller of the IBM Research Laboratory in Zurich that a special class of ceramic materials exhibit superconductivity at 35 ^{o}K has caused a revolution in scientific thinking. The breakthrough by Bednorz and Muller was really two fold. One, the demonstration of a new, previously unrecognized class of superconducting materials. The other, a big advance in increasing the superconducting temperature to a high value believed by many scientists to be unattainable. For this discovery, Bednorz and Muller won the Nobel Prize for 1987.

The new ceramics are based on a particular group of ceramic materials which are based on "pervoskite" structure. The materials are based on lanthanum barium cuprate, $La_{2-x}Ba_xCuO_{4-y}$. By the end of 1986, however, several groups including the IBM Research Laboratory in Zurich, had demonstrated that by substituting strontium for barium, the superconducting temperature T_c could be raised to approximately 40 ^{o}K. The basis for substituting strontium (and calcium) was the knowledge that Ca^{2+}, Sr^{2+} and Ba^{2+} could substitute into La site in the La_2CuO_4 structure and, thereby modify its transport properties. The finding that Sr would substitute for the La and still give rise to superconductivity allowed Bednorz et al., to conclude that the origin of superconductivity produced by the doping was due to a direct electronic mecahnism rather than a size effect. By the application of pressure, the superconducting temperature could be increased to 52 ^{o}K.

The next breakthrough occured in the USA in early 1987 when Prof. Chu of the University of Huston announced that the superconducting temperature could be increased to 92 ^{o}K by substituting lanthanum with yttrium in the structure of the material. Since then there has been a race to develop materials with higher superconducting temperatures as well as process technology to make these materials for commercial applications.

Projected world market for superconductors for the period 1987-2002 is given in Table 29.

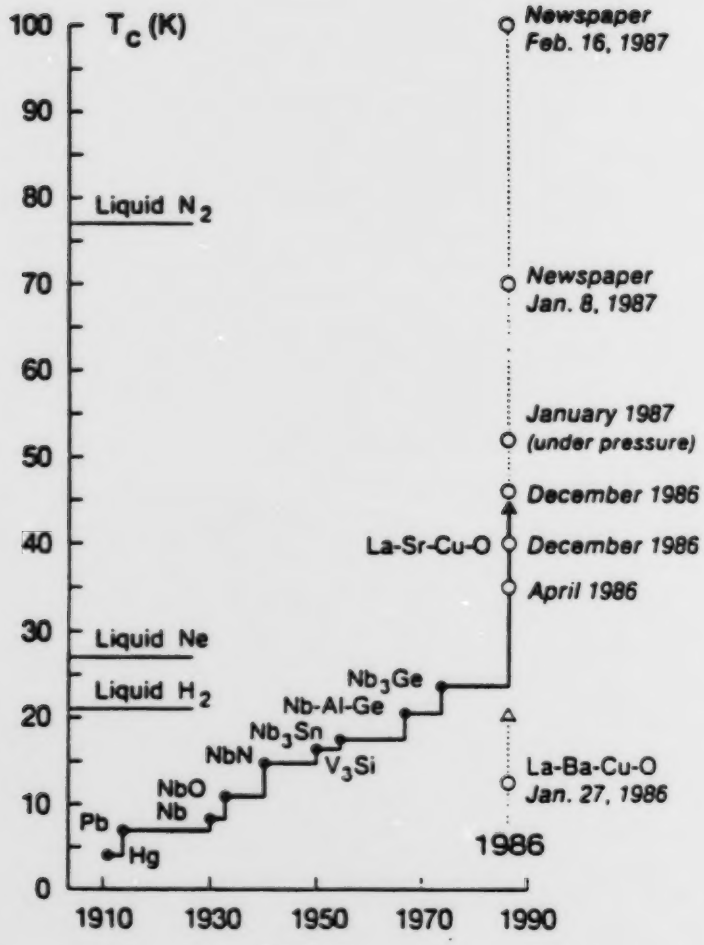


Figure 20. The Increase in Superconductivity Temperature from the Time of Its Discovery in 1911

TABLE 29

Worldwide Markets for Superconductors, 1987-2002

Application	1987 ($ million)	1992 ($ million)	1997 ($ million)	2002 ($ million)
Integrated circuits	25	75	225	400
Lab instruments and sensors	5	25	125	200
Medical diagnosis	150	300	500	750
High energy physics	25	150	150	200
Electrical power	5	10	20	40
Transportation	0	1	5	10
Magnetic separation	5	25	60	175
Total	215	586	1085	1775

Source: *High-Tech Materials Alert*, September 1987.

5. MARKET AND COMMERCIAL STATUS

5.1 General

A number of studies and reports are available in the published literature which project market potential for advanced ceramics based on a number of assumptions and scenarios. In addition, a number of company/industry specific studies have been made by a number of companies, however, these are confidential and are not available for public use. In this discussion, only published information has been used supplemented by discussions with experts.

The available data can be divided into five categories:

- Data for Japan
- Data for U.S.
- Data for the U.K.
- Data for W.Europe
- Data for World Consumption

5.2 Market Data for Japan

The market projection data for Japan made by a number of organizations in 1982 is compared in Table 30. For 1990, the range is from Yen 1,241 trillion to 3,047 trillion. The wide range of values indicates the difficulty and complexity of gathering and interpreting the data because of the technological problems and the associated uncertainties involved in market penetration.

The most widely used data is that projected by the Japanese Ministry of International Trade and Industry (MITI) in 1984 and revised in 1986 given in Figure 21. Three scenarios are presented. First, the minimum projected sales are given in the bottom curve which projects sales of Yen 0.63, 1.3 and 1.8 trillion in the years 1983, 1990 and 2000, respectively. Second, the upper curve is projected on the basis that some of the technological problems can be solved in a timely fashion to achieve market penetration using sales figures of Yen 1.8 and 4.2 trillion yen for the years 1990 and 2000, respectively. Third, the uppermost curve, between the years 1990 and 2000, is projected on the assumption that the use of advanced ceramic components in heat engines will be well established.

MITI officials believe that the sales projections are following the higher line of growth in Figure 21 as of 1985, and expect it to continue. The reliability of these assumptions and projections get a certain degree of support because of the fact that the Japan Fine Ceramics Association subscribes to it.

TABLE 30

Comparison of Market Projection Data for Advanced Ceramics in Japan

(Unit: convert to billions of yen)

Organization / Application		1981	1990				Early 2000s
		*1) MITI survey	*2) Mitsubishi Bank forecast	*3) National Economic Research Association forecast	*4) Toshiba forecast	LTCB forecast	*5) MITI forecast
Electrical and electronic parts		189.8	535.0	669.5 to 799.6	664 to 759	540 or more	2,800 to 4,200
Mechanical parts		40.8	143.0	279.4 to 979.4	266.8 to 920	210	
Transportation machinery (automobiles)	Engines	(non-gas catalyst carriers) 3.5	500			280 to 420	
	(Spark plugs)	37.0	52			52	
Nuclear power		25.0	70	339 to 469		59 to 88	(But, considering the high growth rate in parts and the effects of the spread of technology, the upper limit on the forecasted size of the market is 5 trillion yen.)
(Refractory materials)		-	60		322 to 448.5	-	
Biochemical		1		-	920 or more	100 to	
Total		About 300	1,360.0	1,287.4 to 2,248	2152.8 to 3047.5	1,241 to 1,410	

Notes: *1) "Fine Ceramics Data", MITI Fine Ceramics Office, November 1982
*2) from Mitsubishi Bank Survey Monthly Report No. 338 (June 1983), p. 25, Table 5, case (2)
*3) from "Industry Trends", National Economic Research Association, February 1983, p. 34, Table 3
*4) "Ceramic Industry", Vol. 121, No. 6, December 1983 (figures converted at the rate of $1 = 230 yen)
*5) "Fine Ceramics Basic Issues Conference Report", Fine Ceramics Basic Issues Conference

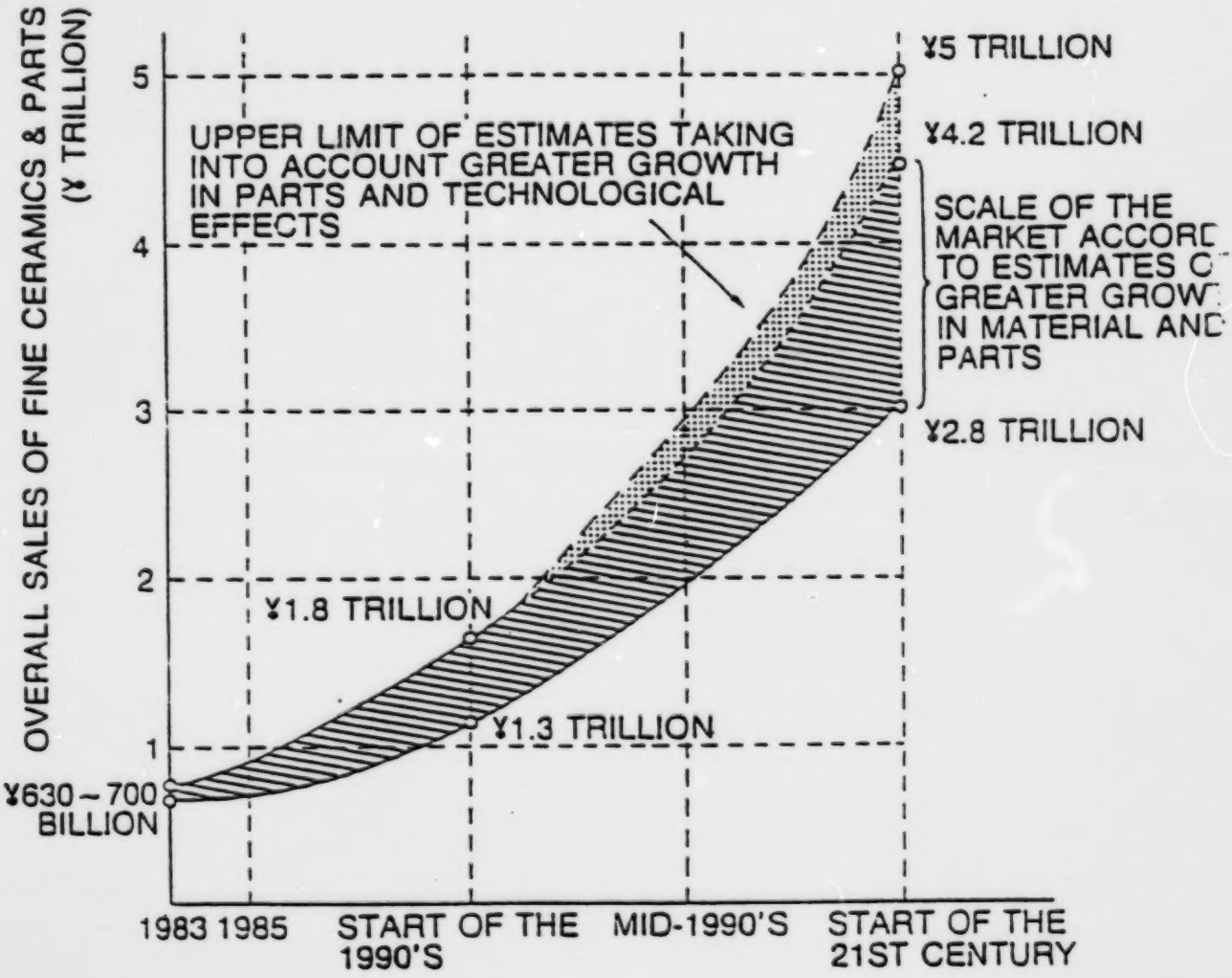


Figure 21. Estimates of the Scale of the Advanced Ceramics (Fine Ceramics) Market in Japan (MITI)

Actual market data up to the year 1987 and projections up to the year 2000 is available form a number of sources and will be discussed.

IBI Inc., Tokyo has studied advanced ceramics market trends and industry structure in Japan(*).

Ceramic Powders

According to the IBI Inc., report, the value of the ceramic powders used in the manufacture of advanced ceramics amounted to Yen 75 billion and is projected to increase to Yen 120 billion by 1991, i.e., an annual growth rate of about 10 per cent. The breakdown of the consumption in terms of type of powder is given below:

	1986	1991
Oxides:	78%	67%
Non-oxides:	12%	20%
Others:	10%	13%

(Note: 1986 figures based on Japan Fine Ceramics Association Data and the 1991 figures are IBI Inc., projections).

The breakdown of the powders in terms of chemical composition is given in Figure 22. The large share of the oxide powders reflect:

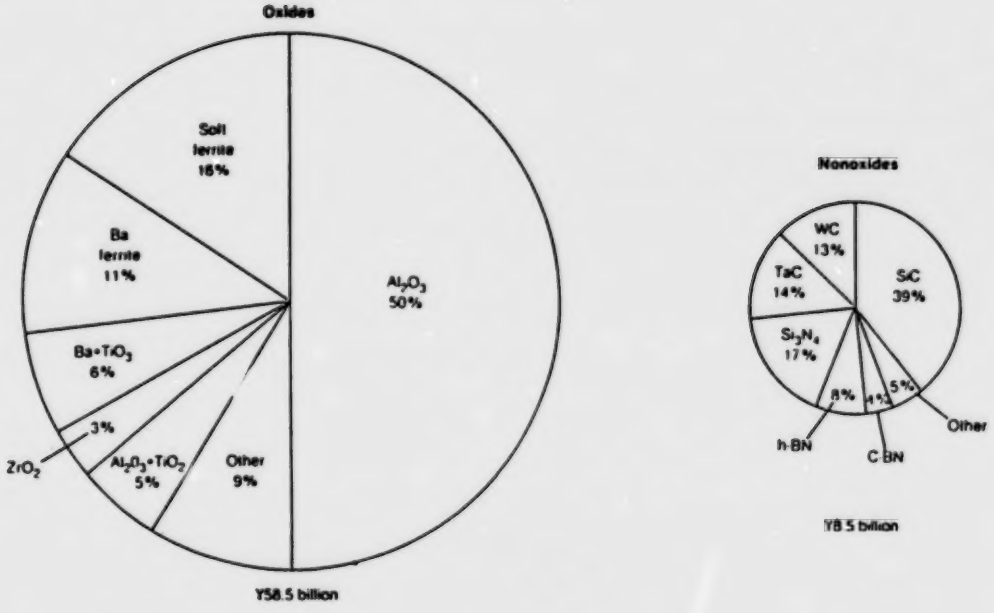
- the importance of alumina (Al_2O_3) for use in IC packages/ /substrates and other electroceramic products;
- the relative lack of development in the engineering ceramic component market, which sees most applications of non-oxide ceramics;
- higher prices of non-oxide ceramic powders in comparison with alumina.

Stability or declines in the prices of alumina powders are anticipated, given the relative maturity of the electroceramic markets. Growth in non-oxide powder production value is expected at a faster pace reaching 20% of the total production by 1991 amounting to about Yen 24 billion i.e., a growth rate of about 13%.

The market data for silicon carbide, silicon nitride and zirconia powders as projected by Mitsui Toatsu Chemical Co., a producer of silicon carbide and silicon nitride powders, is given in Table 31.

---

*"Advanced Ceramics in Japan - Market Trends and Industry Structure,". IBI Inc., Tokyo, 1987.(Prepared for the Canadian Embassy, Tokyo).



Source: JFCA (Japan Fine Ceramics Association).

Figure 22. Breakdown of Ceramic Powder Sales in Japan According to Chemical Composition

TABLE 31

Market Data for Silicon Carbide, Silicon Nitride and Zirconia Ceramic Powders in Japan (Source: Mitsui Toatsu Chemical Inc.)

S i C								Zirconia (Precision Use)			
'84	'85	'86	'90				'95	'84	'85	'87	'90
t/Y	t/Y	t/Y	t/Y				t/Y	t/Y	t/Y	t/Y	t/Y
0	300	390	570	20	30	210	540	0	1.5	150	450
α 210	α 240	α 300	α 720	α 30	α 120	α 450	α 540				
β 40	β 60	β 90	β 360	β 60	β 120	β 240	β 120				
	α -SiC	2,500~20,000 ¥/kg								7,000~25,000 ¥/kg	
	β -SiC	3,000~20,000 ¥/kg		10,000			1,500~3,500 ¥/kg	Price		Powder 3000 ~ 7,000 ¥/kg	
Application	kg/Y	%	Application	kg/Y	%			Application	kg/Y	%	
Heat resistant materials	10,500	42.0	Heat resistant materials	12,000	30.0			Grinding Balls	3,700	49.3	
Wear resistant materials	12,400	30.2	Wear resistant materials	7,000	20.0			Knives and cutters	1,800	24.0	
Corrosion resistant materials	5,800	14.0	Corrosion resistant materials	7,000	20.0			Dies, discs and guide rollers	1,200	16.0	
Miscellaneous	2,400	4.0	Miscellaneous	4,000	10.0			Sensors	2,000	11.3	
								Mechanical parts	300	4.0	
Manufacturers	kg/Y	kg/Y	Manufacturers	kg/Y			kg/Y				
Showa Denko	2,000	2,000	Showa Denko	4,000			12,000				
Toyo Tanso	3,000	3,000	Toyo Tanso	2,000			-	Manufacturers	kg/Y		
Chinetsu Chem.	1,000	200	Nihon Denko	2,000	1,000		-	Tosoh Corp.	4,000		
Taiheiyo Random	900	-	Showa Denko	1,000			-	Daiichi Kigenso	4,200		
Shinano Denki	600	-	Mitsui Toatsu	900			-	Shin Nihon Chem.	1,000		
Seiren			Chubu Kogyo	500			-	Nova Chem.	300		
Fukushima Denko	300	-	Toyo Tanso	500			-	Hokko Chem.	600		
Fujimi Kenmazai	200	-	Fujimi Kenmazai	200			-	Tosoh Japan			
Nihon Denko			Nihon Kagaku					Ishimura			
Mitsui Toatsu			Shinko Denki					Kyowa			
Central Glass			Kyowa					Nihon Kagaku Kogyo			
Ibiden			Ibiden					Nihon Kagaku			

Advanced Ceramic Components

More recent data than the earlier MITI projections for advanced ceramics are available from a number of studies. The actual data for 1985 and projections up to the year 1990 compiled by the Japan Fine Ceramics Association is given in Figure 23. The sales projections show an increase from Yen 10,415 billion in 1985 to Yen 25,262 billion in 1990, to Yen 43,246 by 1995 and to Yen 61,261 by the year 2000 i.e., almost five fold. The electronic and magnetic ceramics market is expected to decrease from 82.5% in 1985 to 67% in 1990 and to 62% by the year 2000. The mechanical-thermal ceramics applications are expected to increase from about 10% in 1985 to about 15% in 1990 to 18 in the year 2000. These projections are in line with the earlier MITI projections.

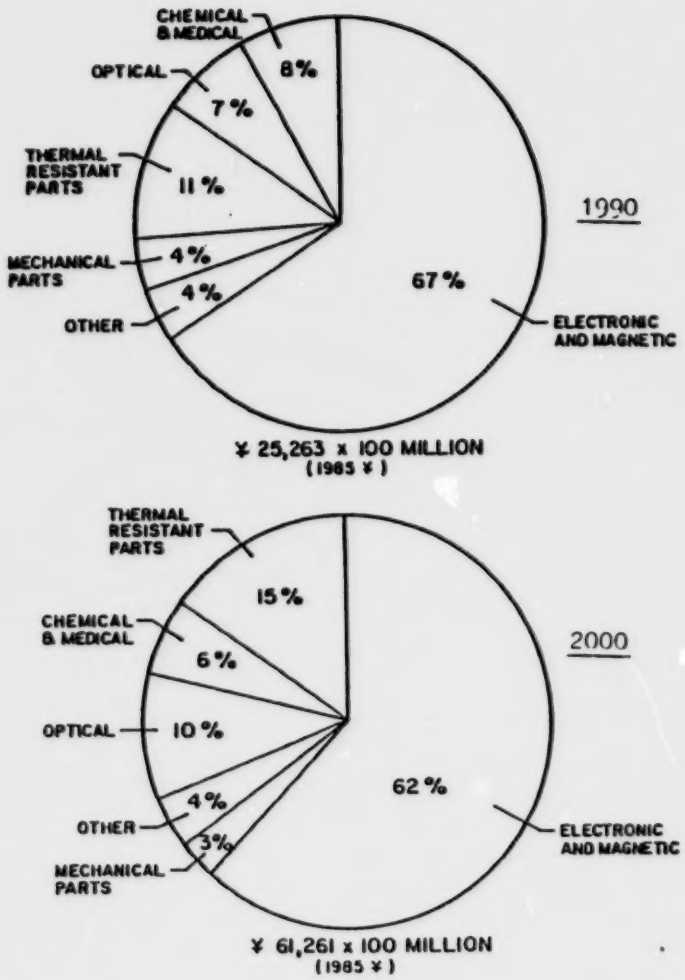
An American study for the U.S. Department of Commerce has evaluated the Japanese advanced ceramics market and the findings are given in Table 32(*). Because of the discrepencies between the products which the Japanese include in their advanced industrial fine ceramics and those of the advanced ceramics industry in the U.S., a direct comparison between the production and consumption figures is difficult. The table shows how the Japanese market for advanced ceramics shapes up, including import/export figures leading to domestic consumption of advanced ceramics in Japan. The potential for penetrating the Japanese market by the American industry is also examined in this report. The individual materials having import potential in the Japanese market are listed in Table 33. The report concludes that the potential is minimal on a realistic scale owing to the total production of advanced ceramics in Japan and the Japanese domestic consumption figures, which have a strong basis in companies vertically integrated from ceramic powder production through end product industries.

Statistics compiled by MITI show that during February 1987, Japan's production of advanced ceramics (fine ceramics) increased 7.2 % from previous month while sales increased 8.4 % to Yen 33,303 million; 30 % of the sales was accounted for by overseas accounts. Exports also showed an increase of 5.3 % over the previous month. The production and sales figures are given in Table 34.

The Japanese electroceramics market is characterized by three important considerations. Firstly, integrated-circuit packages account for just under 40% of the market, followed by capacitors (35%) and piezoelectric devices (16%). The breakdown is given in Figure 24. Secondly, the Japanese markets for electroceramics are well established, and the Japanese companies are leading world suppliers of

---

*Source: "International Market Research Profile of Advanced Industrial Fine Ceramics: Japan,". Prepared for the U.S.Department of Commerce by A.T.Kearney Int'l, Tokyo. Bul.Am.Cer.Soc., Vol 67, No 1, P 58 (1988)



(x 100 million yen)

Classification of products	1985	1990	1995	2000
Electronic & magnetic ceramics	8,586	16,888	26,265	37,668
IC substrates, packages, etc.	481	1,186	2,400	4,680
Thermistors, varistors, etc.	743	1,627	1,960	2,275
Magnets, etc.	1,851	4,339	7,100	10,000
Condensers, piezoelectric parts, etc.	5,314	9,235	14,200	20,000
Spark plugs	257	515	605	714
Mechanical ceramics	580	1,020	1,645	2,082
Tools, hard material parts	453	704	949	1,196
Wear resistant parts	91	230	560	700
Others	36	86	136	186
Thermal ceramics	468	2,771	6,235	9,019
Refractory parts for semi-conductor heat treatment	161	796	1,820	3,800
High temperature corrosion resistant parts	191	1,755	4,143	4,887
Others	111	220	272	332
Chemical and medical ceramics	437	1,912	2,920	3,959
Sensors	318	703	840	975
Catalysts, catalyst carriers	119	209	330	484
Teeth, bones, joints	0	1,000	1,750	2,500
Optical ceramics	229	1,672	4,692	6,342
Optical fibers	197	1,620	4,620	6,250
Others	32	52	72	92
Miscellaneous	175	990	1,489	2,190
Nuclear field	0	590	864	1,340
Others	175	400	625	850
Total	10,415	25,263	43,246	61,261

Source: Private communication from Professor Hiroshi Ioue, President of the Japan Fine Ceramics Association, based on estimates by the Japan Fine Ceramics Association and used with his permission.

(Source. Ceramic Industry, August 1986)

Figure 23 Advanced Ceramics Markets by End-Use Application for the Years 1990 and 2000

TABLE 32

Japanese Advanced Industrial Fine Ceramics Market Trends (US$ millions)

	1984	1985	1986	1991
Monoxides				
Domestic production	1 637.8	1 719.2	2 352.0	4 541.0
Imports	44.2	50.3	57.1	149.3
Exports	500.6	514.8	682.6	1 116.5
Domestic consumption	1 181.4	1 254.7	1 726.5	3 573.8
Silicates				
Domestic production	125.8	135.4	176.5	232.7
Imports	Ngl.	Ngl.	Ngl.	14.9
Exports	37.8	33.5	40.4	20.8
Domestic consumption	88.0	101.9	136.1	226.8
Composite oxides				
Domestic production	1 095.5	1 061.9	1 686.6	2 526.0
Imports	19.0	21.0	25.0	35.7
Exports	354.9	335.8	498.7	630.2
Domestic consumption	759.6	747.1	1 212.9	1 931.5
Nitrides				
Domestic production	106.5	117.0	187.2	756.4
Imports	7.6	9.2	10.7	41.4
Exports	6.3	8.0	11.9	77.2
Domestic consumption	107.8	118.2	186.0	720.6
Carbides				
Domestic production	328.8	336.6	472.5	1 166.5
Imports	21.9	24.8	26.8	69.5
Exports	31.6	33.5	44.0	107.1
Domestic consumption	319.1	327.9	455.3	1 128.9
Other nonoxides				
Domestic production	211.4	225.5	305.4	630.9
Imports	18.9	19.3	26.2	47.6
Exports	50.5	54.5	71.3	118.9
Domestic consumption	179.8	190.3	260.3	559.6
Total				
Domestic production	3 505.8	3 595.6	5 180.2	9 853.5
Imports	111.6	124.6	145.8	358.4
Exports	981.7	980.1	1 348.9	2 070.7
Domestic consumption	2 635.7	2 740.1	3 977.1	8 141.2

Source: International Market Research Profile of Advanced Industrial Fine Ceramics: Japan, Prepared for U.S. Department of Commerce by A. T. Kearney Int'l, Inc., Tokyo, Japan.
Note: 1984, $1.00=237.52 Yen; 1985, $1.00=238.54 Yen; 1986 and 1991, $1.00=168.03 Yen.

(After Bul.Am.Ceram.Soc., Vol 67, No.1, p 58,(1988)

TABLE 33

Sales Potentials for Advanced Industrial Fine Ceramics in Japan

Material	Domestic supplier potential	U.S. supplier potential
Alumina	Good	Good
Magnesia	Good	Fair
Beryllia	Good	Excellent
Zirconia	Excellent	Good
Silica	Good	Good
Zinz oxide	Good	Fair
Tin oxide	Good	Good
Holsteatite	Good	Fair/Poor
Steatite	Good	Fair/Poor
Zircon	Good	Fair/Poor
Mullite	Good	Fair/Poor
Cordierite	Good	Fair/Poor
Spodumene	Good	Fair/Poor
Barium titanate	Good	Fair/Poor
PZT	Good	Fair/Poor
PLZT	Excellent	Fair/Poor
Ferrite (soft)	Fair	Fair/Poor
Ferrite (hard)	Fair	Fair/Poor
Lithium niobate	Good	Fair/Poor
Silicon nitride	Excellent	Fair
Sialon	Excellent	Excellent
Aluminum nitride	Excellent	Good
Boron nitride (hex)	Excellent	Excellent
Boron nitride (cubic)	Good	Fair
Titanium nitride	Good	Fair
Silicon carbide	Excellent	Excellent
Boron carbide	Excellent	Excellent
Titanium carbide	Good	Fair
Tungsten carbide	Fair	Poor
Molybdenum disilicide	Good	Good
Lanthanum hexaboride	Good	Excellent
Titanium diboride	Good	Good
Zirconium diboride	Good	Good
Cadmium sulfide	Good	Good
Molybdenum nitride	Good	Excellent
Amorphous carbon	Good	Good
Graphite	Good	Good
Diamond	Excellent	Excellent

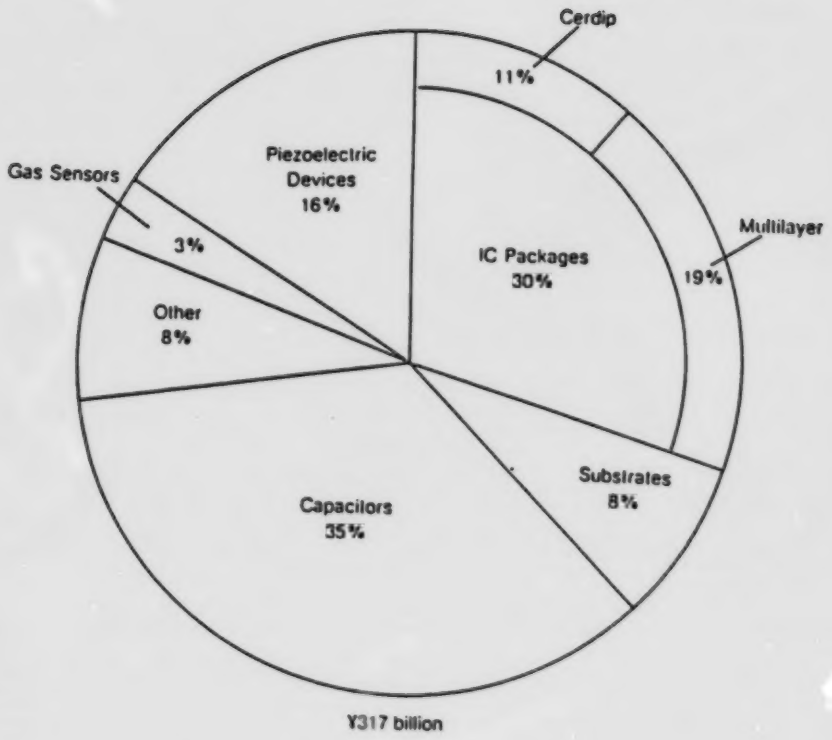
(After Bul. Am.Ceram.Soc., Vol 67, No 1, p 59, (1988)

TABLE 34

Production and Sales of Fine Ceramics in Japan in Feb 1987

	Production		Sales	
	Quantity (1,000 pcs.)	Comparison(%) with January	Quantity (1,000 pcs.)	Value (Yen 1 mil.)
Functional materials	4,466,538	110.4	4,523,873	27,203
IC packages	117,987	102.4	120,384	7,542
Surdips	106,142	103.3	108,819	2,742
Multi- layered IC packages	11,845	94.4	11,565	4,800
Substrates	179,009	93.2	183,681	2,177
Capacitor elements	3,861,419	111.3	3,923,364	9,791
Piezoelectric elements	168,166	123.3	164,419	4,729
Gas sensor elements	1,321	107.4	1,216	1,006
Others	138,636	108.0	130,809	1,957
Structural materials	693,817	90.2	660,364	6,101
Catalyst carriers	24,481	84.9	24,479	1,792
Thermal- resistance materials	42,276	101.1	42,042	1,445
Tools & accessories	533,479	88.4	501,103	945
Anti-abrasive, anti-corrosive materials	68,552	93.9	69,540	1,687
Others	25,029	113.9	23,200	231
Total	5,160,355	107.2	5,184,237	33,303

(Source: Industrial Ceramics, Volume 7, No 3, p170, 1987)



Source: Compiled by IBI from MITI data.

Figure 24. Distribution of Electroceramic Components Produced by Japanese Manufacturers

these high-volume, low-margin products. For example, Kyocera is estimated to supply about 60% of world demand for alumina integrated-circuit packages, and Murata is estimated to supply about 25% of world markets for ceramic capacitors. The leading position of Japanese companies in electroceramic markets is a result of the dominance of Japanese companies in international markets for many varieties of integrated -circuits and other electronic components and equipment. It is reported that the Japanese manufacturers recognize that domestic and overseas markets have reached maturity.

At present the Japanese production of engineering ceramic components is relatively small, about 25% of the electroceramics market. IBI Inc., reports that about 40-50 % of the market consists of test model components and other sample shipments (as of 1986).

With the exception of machine tool bits and catalyst support applications, the market for engineering ceramics in mechanical/ engineering applications is still at an early stage of development. Further, according to IBI Inc., Japanese participants are less optimistic about prospects for the development of engineering ceramics market compared to the years 1984-1985. The 1986 and 1987 Nagoya Ceramic Fairs are reported to be much more subdued than in earlier years; this change in tone is attributed to several factors, including:

- the apparent lack of progress in overcoming certain basic problems concerning high production costs and performance limitations of engineering ceramics;
- the long lead times required to develop component products and markets;
- uncertainty about whether engineering ceramics per se or composite materials - e.g., SiC whisker-reinforced metals or plastics - will be the optimum solution replacing metal components in industrial equipment applications over the long run.

5.3 Market Data for U.S.

For the U.S. advanced ceramics markets, the U.S. Department of Commerce conducted a competitive assesment in 1984(*). The actual and projected shipments of advanced ceramics for the period 1980 - 2000 is given in Table 35. The market situation has changed significantly since that time. The Department is said to be reassessing the industry and the results are expected in 1988.

---

* "Summary of: A Competitive Assessment of the U.S. Advanced Ceramics Industry". T.Schlie and V.Kamenicky. Bul.Am.Ceram.Soc.,Vol 63, No.9. pp 1112-1114 (1984).

TABLE 35

U.S.Shipments of Advanced Ceramics by End Use to the Year 2000
(1980 dollars)

End use	1980		1990		2000	
	$ million	%	$ million	%	$ million	%
Electronics	534	89	1900	75	3485	59
Cutting tools	45	7.5	380	15	960	16
Wear parts	20	3	180	7	540	9
Heat engines	0	0	56	2	840	15
Other	2	0.5	15	1	70	1
Total	601	100	2531	100	5895	100

*Source: Industry Analysis Division, U.S. Department of Commerce.

Results of a number of projections have been published. Available information on these studies will be presented.

For the U.S. advanced ceramic industry, FIND/SVP has recently issued a report on current and future domestic sales (Table 36). Their actual 1986 figures of US$ 2,066 billion does not include advanced ceramics used as insulators, thermistors, resistors, semiconductors, capacitors, industrial recuperators, heat exchangers, cutting tools, gas sensors, bioceramics, and telecommunications. When all of these products are added into the total for 1986, Find/SVP reports the total 1986 advanced ceramics sales in the U.S. as US$ 6.7 billion. Projections of Find/SVP for the advanced ceramic industry sales in the U.S. are also shown in this table. However, with the group of materials previously specified not accounted for in the baseline, this list must be taken as considerably undervalued by Find/SVP's own accounting i.e., at the least $4.7 billion of 1986 sales not listed should grow at the 20% expected for most emerging world market products.

In a study for the U.S. Commerce Department, Technomic, Inc., has estimated the ceramic market for substrates and electronic packages as between $700 and $800 million (Table 37).

The U.S. Shipments of advanced ceramics for the period 1980-1995 has been reported by International Resource and Development Inc., shown in Table 38.

A private industry projection of the growth of advanced ceramics for different applications is given in Figure 25.

Very recently, Business Communications Co. Inc., has projected that shipments of advanced ceramic components for automotive, cutting tool, wear part, heat exchanger, aerospace/defence and biomedical applications will total US$ 2.6 billion in the year 2000. Forecasts for various advanced ceramic market segments are given in Table 39. Average annual growth rates are: 36% between 1987-1990; 22% between 1990-1995; and 18% between 1995-2000. The high rate predicted for the 1987-1990 period is primarily due to large increases in shipments of ceramic cutting tools, wear parts and defence-related components.

5.4 Market Data for U.K.

The United Kingdom market for advanced ceramics also was recently evaluated for the U.S.Commerce Department by Proplan, London, U.K. The results of this study are given in Table 40. Proplan indicates that in the electrical/electronics industry, the U.K. has sufficient domestic supply for its domestic consumption in only the capacitor and resistor production segments, and this is due mostly to U.S. companies setting up production facilities in the U.K. The advanced structural ceramics market in the U.K.is claimed to be satisfied by domestic manufacturers.

TABLE 36

Sales of Advanced Ceramics in the U.S.($ million)

Advanced ceramics with 1986 sales	Actual 1986	Projections in 1986 dollars			
		1990	1995	2000	2005
Electronics	$1 219.0	$3 996.0	$5 244.0	$7 889.0	$9 223.0
Electrical	259.2	370.0	502.0	721.0	1 002.0
All other current products	588.6	746.0	1 190.0	1 670.0	2 265.0
Subtotal	$2 066.6	$5 112.0	$6 936.0	$10 280.0	$12 490.0
Sales for Future Applications of Advanced Ceramics					
Vehicular engines			$3 385.0	$4 509.0	$6 477.0
Integrated optics		$8.0	158.0	1 206.0	2 732.0
Solar energy			100.0	300.0	500.0
Stationary gas turbines			600.0	700.0	900.0
Total U.S. Market	$2 066.6	$5 120.0	$11 178.0	$16 995.0	$23 099.0

Source: High Technology Industrial Ceramics, Find/SVP.

(After Bul.Am.Ceram.Soc., Vol 67, No 1, p 58, (1988)

TABLE 37

Market Value for Electronic Ceramic Products in the U.S.

Component	Value ($ million) 1985	1986	1987
Substrates and packages		700–800*	
Hybrid circuits			
Thick film	597.6'		
Thin film	493.1'		
Multichip	102.7'		
Semiconductor package parts	566.8'		
Ceramic packaged integrated circuits	3420[2]		
Chip carriers	19[3]	27[3]	40[3]
Capacitors			
Total	420[3]	437[3]	460[3]
Fixed: tubular, disk	40.3'		
Stand off	6.4'		
Chips	132.1'		
	89'	104[3]	145[3]
Leaded: radial and axial	312.9'		
Variable: mica, ceramic, and glass	14.8'		
Other	29.1'		
RFI and EMI filters	45.2'		
Feedthrough and bypass filters	8.1'		
Piezoelectric ceramics		63'	
Crystal blanks	74.7'		
Discrete crystals	60[3]	60[3]	60[3]
Microwave ferrites	221.4'		
	50[3]	55[3]	58[3]
Magnetic recording heads	223.8'		
Ferrite devices (nonmicrowave)	81.2'		
	85[3]	93[3]	107[3]
Magnetic tape media	1401.6'		
Chip resistors	26[3]	29[3]	34[3]
Fixed resistors (met/ceram, met/glass, met film)	170.1'		
Resistor networks			
Thick film	163[3]	174[3]	186[3]
Thin film	20[3]	21[3]	23[3]
Thermistor	59.4'		
	69[3]	73[3]	80[3]
Varistor	4.2'		

*Source: Technomic Inc. 'Source: Dept. of Commerce Current Industrial Report MA36Q(85)-1, 9/8. [2]Source: Business Communications Co., Inc. [3]Source: *Electronics*, **60** [1] 51–74 (1986).

(after Bul.Am.Ceram.Soc., Vol 66, No 4, P 637, 1987)

TABLE 38

U.S. Shipments of Advanced Ceramics (1980 - 1995)

	1980	1985	1987	1990	1995
GNP (Bil $)	2632	3895	4530	5700	8100
% Advanced Ceramics	0.035	0.038	0.043	0.058	0.081
Advanced ceramic shipments ($ million)	830	1465	1940	3325	6590
Electronics/magnetics	740	1300	1660	2715	4910
Mechanical	70	115	195	450	1300
Heat engines and parts		neg	5	120	620
Cutting tools	45	65	120	210	450
Wear parts	25	50	70	120	230
Chemical applications	neg	10	35	70	140
Space hardware	10	20	25	40	80
Integrated optical devices			neg	10	90
Biomedical applications	5	10	15	25	50
Nuclear power applications	5	10	10	15	20

Source: International Resource and Development Inc., Advanced Ceramics Market Opportunities report.

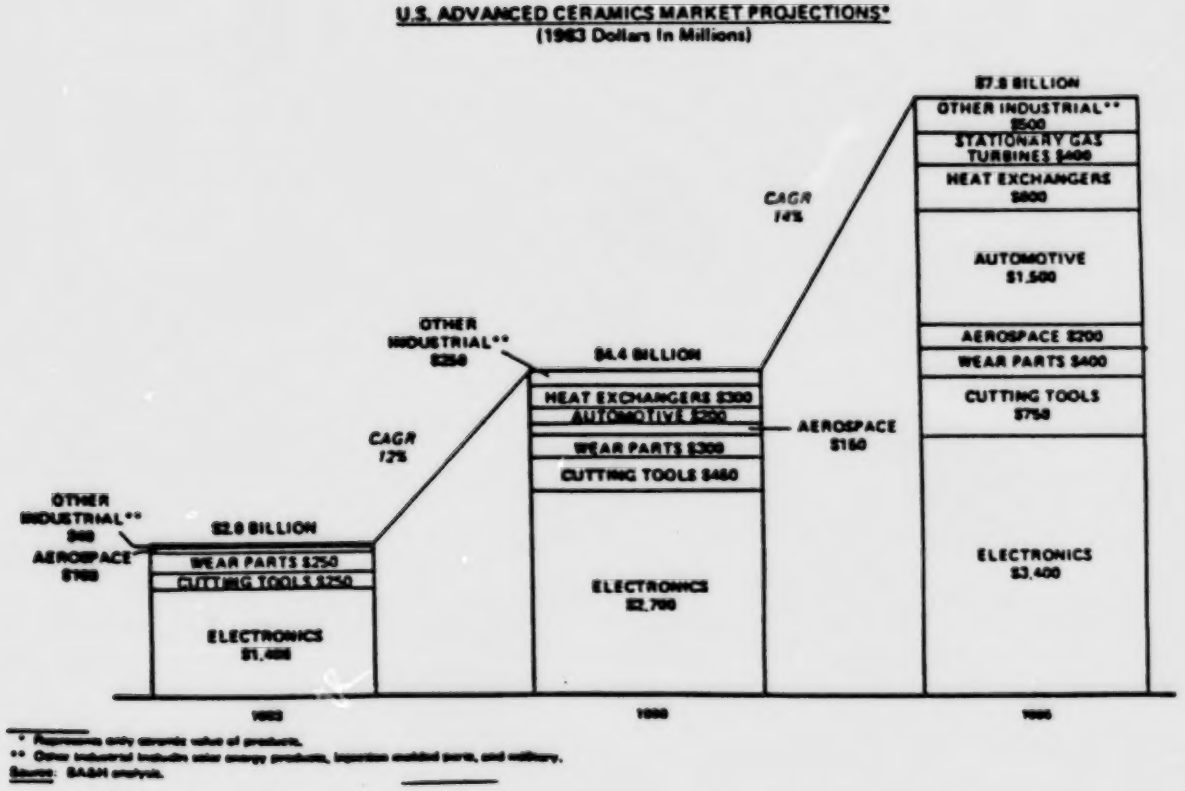


Figure 25 . A Private Industry Projection of US Market for Advanced Ceramics

TABLE 39

U.S.Markets for Advanced Structural Ceramics
(in millions of current dollars)

	Year							
	1987		1990		1995		2000	
Automotive/heat engines	29	(17%)	81	(19%)	310	(27%)	820	(31%)
Cutting tools	32	(18)	92	(21)	246	(21)	500	(19)
Wear parts, other industrial	75	(44)	150	(35)	320	(28)	720	(27)
Heat exchangers	7	(4)	15	(3)	50	(4)	100	(4)
Aerospace, defense-related	20	(12)	80	(19)	200	(17)	445	(17)
Bioceramics	8	(5)	15	(3)	34	(3)	60	(2)
Total	171		433		1160		2645	

Source: Business Communication Co. Inc

(after Ceramic Industry, p 10, January 1988)

TABLE 40

U.K.Consumption of Advanced Industrial Fine Ceramics (US$ million)

Market	1983	1984	1985	1986	1987
Electrical/electronics	142.9	141.1	151.7	190.9	252.7
Heating and energy industrial equipment	2.66	2.42	3.04	3.37	5.13
Chemical/petroleum	7.3	7.1	7.28	8.65	10.58
Motor industry					
Metal-working industry	4.94	4.73	5.12	6.6	10.03
Other equipment	5.62	5.78	6.48	8.37	1.12
Total	163.42	161.13	173.62	217.89	289.56

Source: Profile of the U.K. Market for Advanced Industrial Fine Ceramics, ProPlan, London, U.K.

(After Bul.Am.Ceram.Soc., Vol 67, No1, p 59, (1988)

Proplan cites the strong market position that Lucas Cookson has with its Syalon licences and various structural components as dominating the industry.

5.5 Market Data for W.Europe

Frost & Sullivan Ltd.,(*) of London, U.K., has recently projected that the European market for advanced ceramics will reach US$ 2.2 billion by 1992, i.e., an increse of more than 50% from the 1987 level of US$ 1.4 billion. According to the report, ceramics, particularly technical ceramics, are assured of rapid growth in the next 20 years or more. Heat engine parts, electronic components and medical prostheses are among the application areas with high growth potential.

Currently, electronics is Europe's largest ceramic market segment: US$616 million in 1977 (44% of the total), Capacitors are today's largest end-use, but integrated circuit packages will post the highest growth rate among electronic applications (about 30% /year). Second largest segment is refractories at 28% of the 1987 total. The engine parts segment, now at a "negligible base," will experience the most rapid growth, clipping along at 40% per year.

Among advanced ceramic materials, the report says alumina and titanates will dominate. High growth rate honours, however, will go to silicon nitride. The market projection on the rate of growth of advanced ceramics in Europe is given in Figure 26.

5.6 Market Data for World Consumption

A study by Fredonia Group Inc.,(**) addresses the worldwide advanced ceramic sales for the period 1977 to 1995. According to this study, the sales of advanced ceramics increased from US$ 905 million in 1977 to US$ 5.4 billion in 1986, an annual growth rate of 22%. Projected sales are US$ 12.2 billion by 1991 and US$ 24.5 billion by 1995. Table 41 summarizes the market data and projections of this study, both by end use and by countries.

It is interesting to note that this is the only study that gives market data for Canada. It also projects that the world growth rate for advanced ceramics is 20%; that the U.S. will maintain its average growth rate; and that Canada and Japan are expected to show the highest growth rate.

---

*"Ceramics Thrive in Changing World Markets,". M.Schober. Bul.Am.Cer.Soc., Vol 66, No 12, pp 1698-1699 (1987).

** "Advanced Ceramics in Europe: $ 2.2 Billion Market by 1992," Ceramic Industry, P16, January 1988.

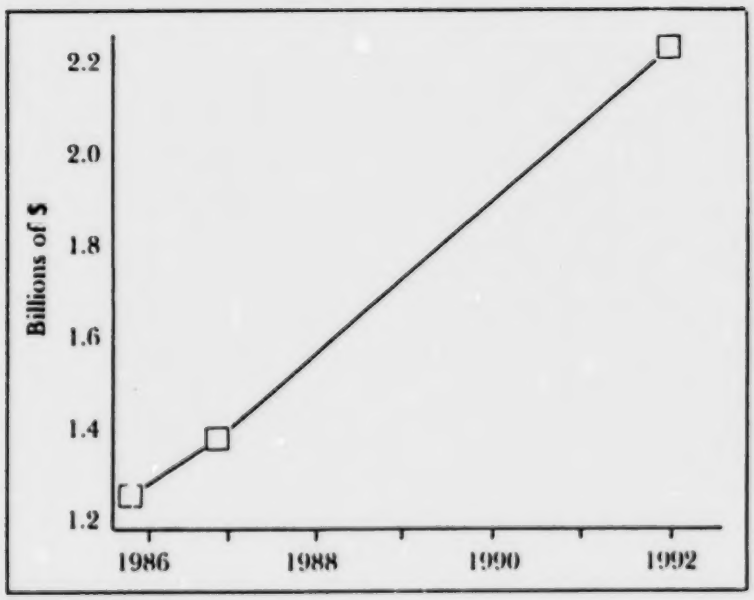


Figure 26.Growth of Advanced Ceramics Market in Europe

(Source: Frost & Sullivan Ltd., London)
(After Ceramic Industry, P 16, January 1988)

TABLE 41

Worldwide Advanced Ceramics Sales by Region, 1977-95

Region	1977 ($ million)	1986 ($ million)	1991 ($ million)	1995 ($ million)
Japan	398	2 587	5 900	12 100
United States	362	2 024	4 500	8 650
West Germany	42	254	550	1 100
United Kingdom	38	167	390	825
France	32	151	335	675
Other Western Europe	15	90	195	400
Canada	10	72	170	375
Other	8	63	160	375

Source: The Freedonia Group, Inc.

Product	1977 ($ million)	1986 ($ million)	1991 ($ million)	1995 ($ million)
Electronics	813	4 808	10 820	21 375
Cutting tools	58	433	885	1 625
Heat engines	0	neg	80	675
Other	34	167	329	825
Total	905	5 408	12 200	24 500

Source: The Freedonia Group, Inc.

(after Bul. Am.Ceram.Soc., Vol 66, No 12, 1987)

5.7 Commercial Application Status of Advanced Structural Ceramics

The most important commercial applications for advanced structural ceramics can be grouped into two categories:

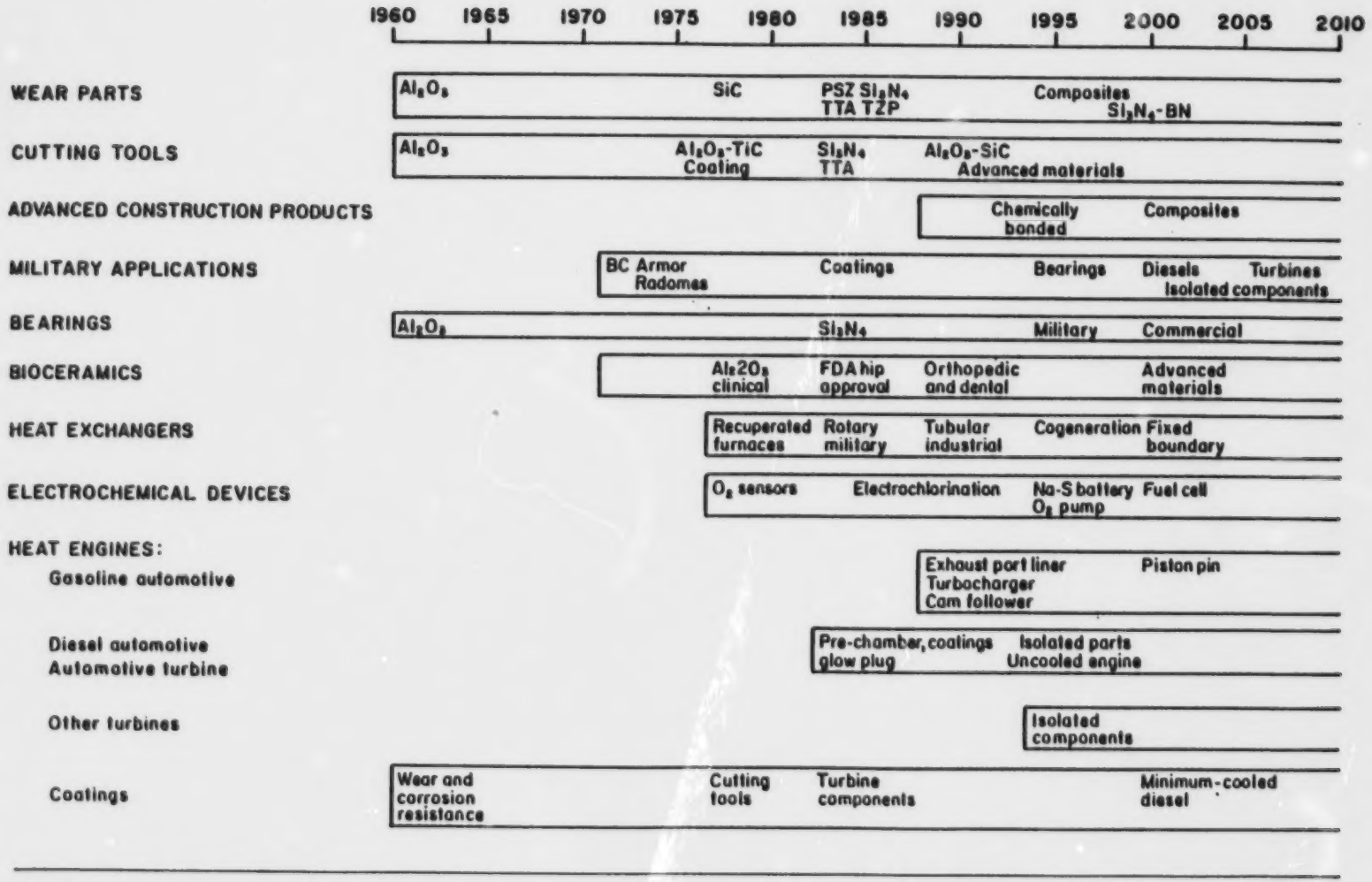
- Heat Engine Applications
- Industrial Applications

5.7.1 Heat Engine Applications

As discussed earlier, advanced structural ceramics originally received importance for two reasons: (i) as replacement materials for metals to improve energy efficiency of engines by increasing the opertating temperatures; and (ii) strategic considerations, i.e., ability to replace strategic metals such as chromium which are needed in the present generation of gas turbine engines. Technology development, which started in the early 1970's, has taken longer than expected because of the problems associated with the brittle nature of ceramics, as well as the ceramic processing problems associated with reproducibility in manufacturing, reliability in service and cost. Partial success has been achieved in these areas which permit the first generation components to be used for a limited number of applications. However, until cost-effective solutions are found for commercial manufacturing, market acceptance and penetration for automobile engine applications - which is the most impportant commercial market- are not expected to reach projected levels. One estimated scenario for the incorporation of ceramic components in various structural application categories is shown in Figure 27.

Gas Turbine and Jet Engines

The development of prototype gas turbine engines is taking place in the United States, W.Germany and Japan. Historically, the U.S. Army and the U.S.Department of Energy (DOE) started the development work on ceramic components for gas turbine engine applications in the early 1970's. Although significant achievements have been made, particularly with regard to engineering design with brittle materials, to date the programs have not been successful in terms of providing technological solutions which could lead to commercialization. In fact, the delays in the development of ceramic gas turbine engines in U.S. Dept. of Energy sponsored research has contributed to growing disappointment in advanced ceramics. Recently, the advanced gas turbine projects (AGT 100 and AGT 101), which were designed to develop ceramic gas turbines capable of operating at combustion temperayure of 1300 C, concluded without testing at the designed operating temperature capability. The major short comings of the 5-year development project were the limitations of the ceramic materials, both in physical property reliability and operating temperature. Despite the inability to test at



SOURCE: David W. Richerson, "Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report prepared for the Office of Technology Assessment, December 1985.

Figure 27. Estimated Scenario for Implementation of Ceramic Components in Structural Application Categories

the design conditions, the projects are being continued under the designation Advanced Technology Turbine Applications Program. Materials development and testing at temperatures and parameters approaching the design conditions, as well as nondestructive evaluation technology for components, will factor heavily in this new 5-year program.

In W.Germany, the development of gas turbine engines was initiated in the 1970's with financial assistance from the government, and technology support from industry, universities and R&D establishments. A few all-ceramic prototype engines were built and demonstrated. Commercialization, however, is not expected before the 21st century, if then.

The development of ceramic-component based gas turbine engines has been in progress in Japan for a number of years. MITI has recently started an eight-year national program at a cost of Yen 20 billion. Companies involved in the development include: Toyota, Nissan, and Mitsubishi. The project aims to manufacture two prototypes, one for trucks and one for cars.

In the U.K., a consortium of industrial companies led by Rolls Royce is involved in the development and use of ceramic components for gas turbine engines with financial support from the government. Details of progress of work are not available.

In Canada, Pratt & Whitney are evaluating the use of ceramic components for stationary applications in some of their jet engines. It is an R&D project designed for test and evaluation purposes. Commercialization is not expected in the immediate future.

Advanced ceramic coatings have been used for more than a decade in commercial and military jet engines to achieve high temperature corrosion resistance, erosion resistance and thermal barrier protection for metal components. Plasma technology is used for coating the metal parts and components. Over the years, different materials have been used, e.g., alumina, spinel etc. New material combinations are being developed on a continuing basis by vertically integrated equipment/material developers/suppliers such as Metco Co. Thermal barrier coatings based on stabilized zirconia have achieved commercial acceptance.

Indications are that the use of coatings in general, and plasma coatings in particular, will increase to meet demand requirements. Because of safety considerations, the specifications for coatings, both materials and deposition technology, are controlled by aircraft and engine manufacturers. Companies providing plasma coating services have to meet rigid qualification/quality criteria established by the original equipment manufacturers.

Automotive and Truck Engines

The world leaders in the development and commercialization of advanced ceramics for engine applications are Japanese companies. Work has been in progress for almost a decade starting from the late 1970's. Automobile manufacturers joined forces with ceramics manufacturers to develop ceramics for engine applications as shown in Table 42. The euphoria of the early 1980's appears to have waned due to technological and cost problems, however, particularly for the development and commercialization of all-ceramic engines; Isuzu appears to be the only company still pursuing this goal.

Notwithstanding problems with the all-ceramic engines, the Japanese auto manufacturers appear to have maintained their long term interest in incorporating ceramic components in engines. The trend towards the use of non-oxide engineering ceramic components in Japanese vehicles is shown in Figure 28.

Diesel engine technology development primarily revolves around improvements in the fuel efficiency of the engine. In general, this means reducing the heat loss in the engine through better thermal insulation and recovering as much of the exhaust heat energy as possible. These concepts are referred to as: ceramic or uncooled engine; the adiabatic engine; and turbocompound engine. Ceramic parts/components for diesel engines currently in production or pre-production include:

- glowplugs
- precombustion chambers
- rocker arm components
- valves and valve guides
- valve seats
- exhaust port liners
- cylinder heads
- head underside plate
- turbocharger

Many of these parts are common to both diesel and gasoline engines, and it can be expected that commercialization will take place concurrently. Changes in industry structure are likely to result in increased use of imported diesel engines as Europeans and Japanese companies form joint ventures with North American vehicle producers.

The most important developments in gasoline engine technology which have a bearing on advanced ceramics usage are: multi-valve technology, lean-burn technology, and four-cylinder engines. Use of ceramic components are expected to contribute benefit in terms of: frictional loads, stronger pistons to achieve higher compression ratios, and reduction in mass. A recent analysis of near term potential

TABLE 42

List of Joint R&D Programs between Japanese Auto Manufacturers and Ceramic Component Manufacturers

CERAMICS MANUFACTURERS	AUTO AND AUTO-PARTS MANUFACTURERS
Kyocera	Isuzu Motors (Ceramic Engines) Nippon Piston Ring (Power mechanism parts) Shibaura Electronics (Temp sensors) Fujikin (Valves)
Asahi Glass	Mitsubishi Motors (Auto parts)
Toshiba Corporation	Toyota Motor (Ceramic gas turbine engine) Komatsu Ltd., (Ceramic Diesel Engine)
Toshiba Ceramics	Tokuyama Soda (Tokuyama Ceramics)
NGK Insulators	Cummins, USA (Ceramics for Diesel Engines)
Hitachi Chemicals	Nissan Diesel Motor (Ceramics for Diesels)
Hitachi Metals	Koransha (Providing Koransha technology) Lucas-Cookson Sialon (Technology acquaition)
Filton	Mitsui Engineering & Shipbuilding (Development of porous ceramic parts)
Shinagawa Refractories	Souther, USA (Acquistion of fiber tech.)

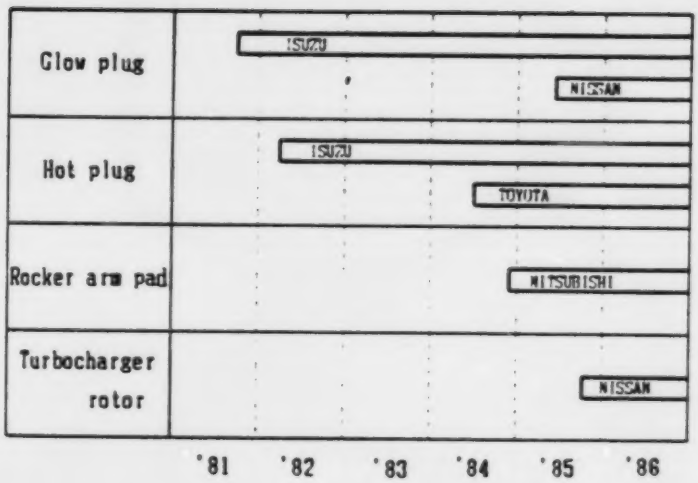


Figure 28. Trend toward Increased Use of Advanced Structural Ceramics in Japanese Automobiles

of ceramics in gasoline engines indicates that the most promising applications are valve-train components and piston components operating in the temperature range 400-600 °F.

As is to be expected, all the present commercial manufacturers of advanced ceramic components for engines are Japanese ceramic companies such as NGK Insulators and Kyocera, who have established relationships with the Japanese vehicle manufacturers for over a decade with joint R&D projects. In fact, this is the reason behind Japanese success in the early commercialization of ceramic components in engines in Japan.

In North America, the situation is quite different. Whereas Ford Motor Company has been involved in the in-house development of ceramic component development for more than a decade, the automobile manufacturers (G.M., Ford., Chrysler) have not participated in joint R&D programs with ceramics manufacturers as in Japan. This position appears to be changing. Many of the present important autoparts manufacturers are active in establishing joint ventures to develop ceramic components and commercialize them, e.g., TRW-Norton, Eaton-GTE, Ford-Ceradyne, Garret-Ford. This can be attributed to the policy of the North American auto manufacturers introduced after the 1982 recession, i.e., the autoparts manufacturers are expected to increase their share of R&D in the development of components and systems.

The most optimistic projections have been made recently by Richard A. Alliegro of Norton Company(*), who is also the President of the United States Advanced Ceramics Association. He states:"1988 will be a watershed for advanced ceramics. Look forward to significant technical achievements, increased market opportunities and the beginning of broad and in-depth understanding of the engineering opportunities of such high performance ceramics as silicon nitride, silicon carbide, alumina, and zirconia.

For example, expect major progress in the development of ceramic components for internal combustion engines - intake and exhaust valves, valve seats, exhaust port liners, turbocharger rotors and portions of reciprocating piston assembly. A case in point: Buick's 1988 Grand National boasts of a ceramic turbocharger rotor. In addition, a set of ceramic valves is being road tested in an Oldsmobile Cutlas Ciera".

This optimism is attributed to: substantial progress made by the ceramic material producers toward solving problems of property predictability, long-term reliability and environmental sensitivity. Now, for the first time, design engineers can confidently include advanced ceramics among candidate materials for an ever-lengthening list of applications previously dominated by metals and polymers.

---

* "Ceramics: powerful weapon in designer's materials arsenal". Richard A. Alligero. Editorial, Ceramic Industry. February 1988.

5.7.2 Industrial Applications

The commercial status of industrial applications of advanced structural ceramics can be grouped into the following categories:

. Cutting Tools

. Wear/corrosion parts

. Heat Exchangers

5.7.2.1 Cutting Tools

Ceramic cutting tool tips were first used during World War II and development work has since aimed at producing materials with increased strength, hardness and shock resistance that can be manufactured to provide consistent, predictable and uniform performance. It is perhaps the latter that has prevented more widespread acceptance of silicon nitride and the sialons but both are now rapidly shedding the stigma of alumina with various additives. They retain strength and hardness to a greater degree than the carbides but due to lack of toughness they are generally limited to uninterrupted cuts at relatively low feed rates and cutting depths. Sales in the USA are estimated at some US$ 20 million - or a little over 2% of the market for carbides and sales in Japan are estimated to be be of the same order though production is larger because Japan also supplies to the U.S. market. Sales in W.Europe are again probably of the same order or even higher as ceramics were adopted earlier than elsewhere due to difficulties in obtaining supplies of tungsten following World War II.

The new generation of cutting tool materials includes not only silicon nitride and the sialons but also alumina reinforced with either titanium carbide, titanium nitride or zirconia, cubic boron nitride, polycrystalline diamond and most recently alumina reinforced with silicon carbide whiskers. These materials cannot, however, be substituted directly for the traditional maaterials because they require machine tools that can take advantage of the higher cutting speeds that they allow.

Over the period 1968- to 1981 the U.S. cemented carbide industry sales increased from US% 300 million to US$ 980 million but the sales slipped to US$ 600 million in 1983. In W.Europe the sales fell 20-30 %, however, in Japan the sales appear to have remained the same. Since then there has been little growth despite an increase in industrial output. This has been attributed to a combination of improved performance and longer life of the new cutting tools introduced. The many factors changing the traditional market include:

- improved properties of cutting tools by way of deeper cut and longer life and improvements in near net shape manufacture of parts, which have reduced demand

- improved properties are also extending the range of usage- new materials being used in aerospace, electronics and other industries require these new cutting tools

- the advantages of improved performance such as higher cutting speeds and increase depth-of-cut are resulting in companies equipping with NC and CNC machine tools capable of using the high performace tools effectively

Published studies indicate that the sales of ceramic cutting tools will double by 1990 and achieve a 5% market penetration, increasing to about 20% penetration by the year 2000. Within the advanced cutting tools market silicon nitride and sialons are expected to improve their position.

Materials that are machined comprise mainly of various grades of carbon, stainless and alloy steels and gray, ductile and malleable cast irons. While coated carbide inserts are used in the main, the advantages of using ceramics is that cutting speeds can be increased significantly. In the machining of gray cast iron for example - a material used in considerable quantities in the automotive and other industries - the cutting speed of silicon nitride is about three times that of coated carbides and almost twice that of alumina. Also, as hardness increases the effectiveness of coated carbide diminishes significantly whereas higher toughness ceramic tools continue to perform well. The toughness of silicon nitride also makes it suitable for milling; at a cutting speed of 35 metres/second tool life is three times that of coated carbide at 30 metres/second.

Sialon cutting tools are even tougher than silicon nitride. Their main areas of application are the machining of high temperature alloys and the turning of cast iron. A peculiarity of the material is that tool life is extended when the removal rate is increased as the amount of energy absorbed by the tool is such that a plastic thermal cutting mechanism occurs on the component surface.

One of the earliest users of sialon cutting tips was Rolls Royce Ltd., in the U.K. under a collaborative arrangement with Lucas. The original use was on titanium. By 1981 Rolls Royce was able to make considerable savings by taking advantage of the 10-fold increase in metal removal rates. It is reported that instead of six machining centres- each costing over US$ 1 million, only four were required. Syalon cutting tools have been used to turn aeroengine compressor discs made of high temperature nickel alloys by machining on both sides simultaneously to prevent distortion.

Syalon 101 has been produced by Lucas Cookson Syalon Ltd., since the late 1970's and its most successful application has been as an indexable lathe insert for cutting metal. Licence agreements have been made with Kennametal Inc., in the U.S. and Sandvik AB in Sweden and the U.S.

In the U.S. there are five main producers of silicon nitride cutting tools. They are:

- GTE Products Corporation Walmet Division
- NTK Cutting Tool Division of NGK Spark Plugs Inc
- Iscar Metals Inc (based on licence from Ford)
- American Feldmuehle Corporation
- Norton Company (Noralide NC-132)

The GTE Quantum 5000 inserts consisting of silicon nitride and alumina, yttria and titanium carbide have been under test since 1974 and are commercially well accepted. A similar material, but without titanium carbide, is used by Iscar.

There are also two manufacturers of sialon cutting tools - Kennametal Inc., and Sandvik Inc., both under licence from Lucas Cookson.

Another producer is the Greenleaf Corporation which uses a composition of silicon nitride, titanium carbide and alumina.

In W.Germany, Electroschmeltzwerk Kempten (ESK) manufactures cutting tool inserts of EKasin Z. The SKF Division of Feldmuhle AG has manufactured cutting tools based on silicon nitride since 1983.

In Sweden, ASEA Cerama AB concluded an agreement in 1985 whereby Seco Tools, a Sandvik subsidiary, was granted an exclusine licence to use glass encapsulation and HIPing technology dveloped by ASEA for the manufacture of silicon nitride cutting tools. Since 1985 KemaNord Industrikemi AB has supplied powders for cutting tool applications and AE Developments Ltd., in the U.K., has supplied a similar product-Nitrasil S.

In Japan, producers of silicon nitride cutting tools include:

- Hitachi Metals Company Ltd
- NGK Spark Plug Company Ltd
- Nippon Tungsten Company Ltd
- Toshiba Tungaloy Company Ltd

Dijet Industrial Company is reported as collaborating with Kennametal in marketing sialon tools.

5.7.2.2 Wear/Corrosion Parts

As components in machinery and in industrial systems, advanced ceramics are finding increased use to overcome abrasion/wear/corrosion problems. Some of the important applications are:

- Ball and Roller bearings
- Extrusion and Tube drawing dies and plugs
- Precision jigs and fixtures
- Pumps, seal faces and other mechanical parts
- Cyclones and chutes
- High temperature industrial fans
- Nozzles for erosive/corrosive applications

Typical applications of advanced ceramics in Cement, Coal fired power, Coal preparation, Grain handling/storage, Mining and mineral beneficiation, Sand & gravel, and Iron & steel industry are shown in Figure 29. Similar applications are found in Foundry, Glass, Pulp & paper, Solids recycling industries.

It must be pointed out that, from a material point of view, alumina, zirconia (PSZ), silicon nitride, sialons, and silicon carbide are competing with each other for many of the foregoing applications. The ultimate selection and use depends not only on the material properties but also on the reliability/availability of the required components, the engineering service provided by the manufacturer/vendor of the materials, cost and performance in use.

To date, all the materials are finding increased usage, however, the competition between silicon carbide, silicon nitride and the sialons is very keen. The use of silicon nitride, sialons and silicon carbide will be discussed briefly.

Silicon Nitride and Sialons

Ball and Roller Bearings

Hot pressed silicon nitride was selected early on as a cncandidate material for rolling elements and races because of its high-temperature strength, light weight, high hardness, low friction and good fatigue life. The capability of operation in the dry state, should lubrication be interrupted, is of value as is the material's high fracture strength.

The early development work was carried out by Norton Co in the U.S., SKF in Sweden, and RIV-SKF in Italy for engine applications. It is reported that Pratt & Whitney, General Electric, Rolls Royce, Aerospatiale, Agusta, Messerschmidt-Boelkow-Blohm, Sikorosky, Boeing

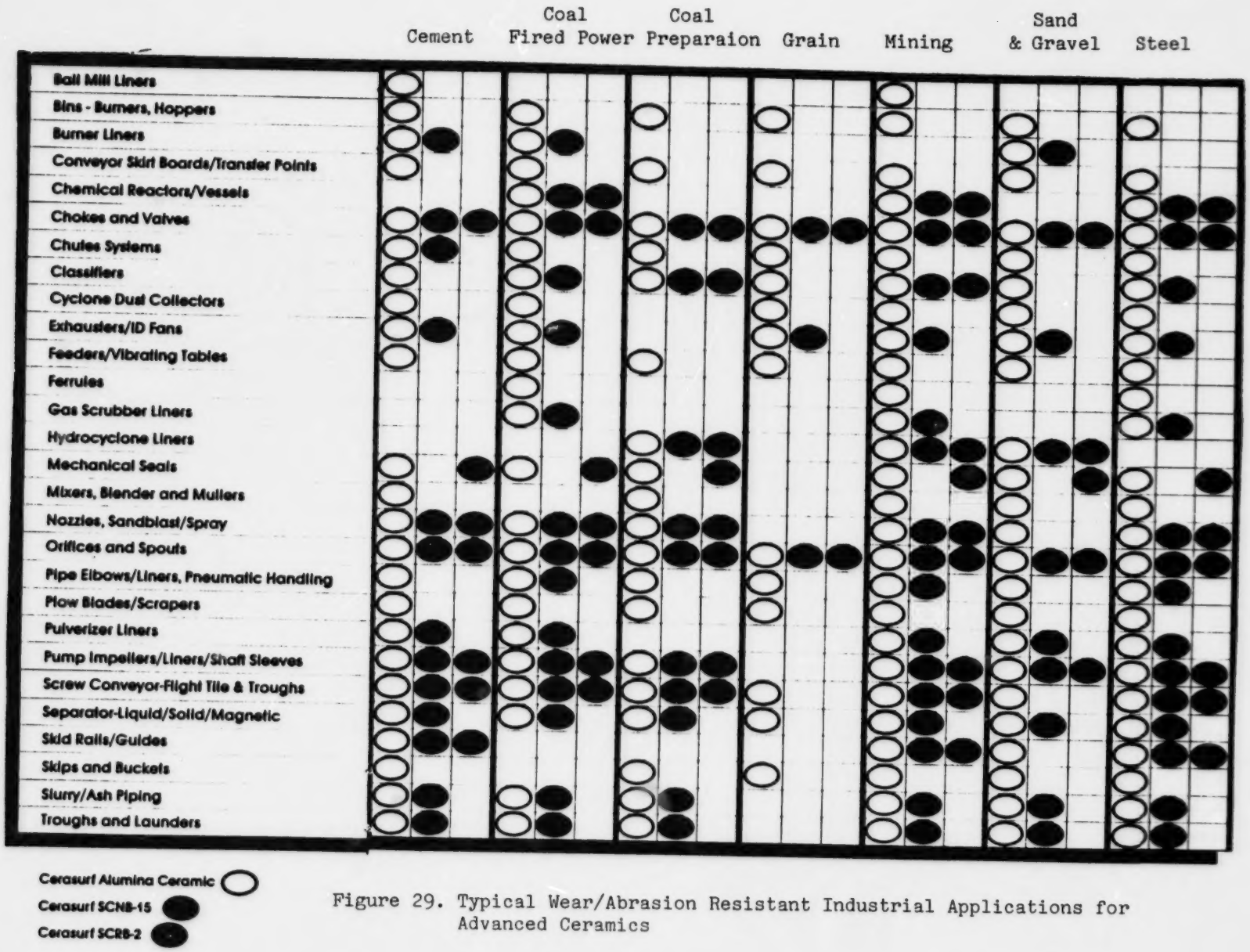


Figure 29. Typical Wear/Abrasion Resistant Industrial Applications for Advanced Ceramics

Vertol and Westland have chosen silicon nitride as the prime material for experimental bearings. Other applications include: diesel engine bearings, electric discharge machining and in the manufacture of semiconductor.

Precision ball bearings became available in 1986 from Norton Co., and are supplied both in ball and roller shapes. In the U.K. Spheric Engineering Ltd., has added silicon nitride to its range of materials.

In Japan, Toshiba has been developing silicon nitride bearings and, in 1985, reported the availability of heat/corrosion resistant bearings in association with Koyo Seiko Company Ltd.

Syalon bearings are being developed and perfected by Lucas Cookson Ltd., in the U.K.

Extrusion and Tube Drawing Dies and Plugs

Silicon nitride and sialons have been used since the early 1970's as plugs and dies in the manufacture of stainless steel and other tubes. Materials used for cold drawing have evolved through the traditional hard chrome plated steel and tool steel to the tungsten carbide/cobalt materials to silicon nitride/sialons. In the U.K. the Tube Investments Group is reported to be using silicon nitride plugs since the 1970's to draw some 2 million metres of tube each year. Sialons also have been used by the company.

The competition between silicon nitride, sialons and zirconia (PSZ) is keen for these applications.

Precision Jigs and Fixtures

Reaction bonded silicon nitride is used by many industries in applications that require resistance to thermal shock, long term dimensional stability at high temperatures, resistance to attack by solders and fluxes, and good oxidation and wear resistance. Bulk of the uses are in the manufacture of semiconductor/electronic products.

Pumps, Seal Faces and Other Mechanical Parts

Various forms of silicon nitride as well as sialons are used for various wear/corrosion resistant applications as components such as face seals, bearing and shaft sleeves for pumps and flow meters, wear plates and nozzles, wire guide pulley inserts and ring gauges. The present market for these uses has been estimated at US$ 500 million.

Sohio Engineered Materials Co., manufactures over 200 sizes and configurations of slurry pump parts from silicon nitride bonded silicon carbide used in mineral processing, utility and specialty chemical

industries. Cast parts are reported to outlast metals by 2-fold to 20-fold. The Worthington Pump Division of Dresser industries Inc., produces pumps with silicon nitride/silicon carbide liners to improve wear resistance when pumping slurries, cemented into cast iron outer shells.

Parts made of reaction bonded silicon nitride are being successfully used for:

- handling hot acids, acidic slurries and sea water mixtures as well as dry abrasive particles;
- as pump bearings in contact with hot phosphoric acid, phosphorus oxychloride and nitric acid;
- as acid dipping spools in nitro-sulfuric acid mixtures;
- as butterfly valves in hot abrasive gas flows; and,
- as powder spray nozzles in the manufacture of detergents.

Sialons are also finding increased applications, particularly for rotary sealing applications. A sialon composite with 10% boron nitride is being used for brake rings in a horizontal continuous caster by Nippon Kokan KK in Japan.

U.S., European and Japanese manufacturers of silicon nitride and sialon products are listed in Tables 43, 44 and 45, respectively.

Silicon Carbide Products

Historically, the industrial uses of silicon carbide can be grouped as: abrasives, refractories, metallurgical, and other. Estimated consumption of silicon carbide by end use for the Western industrialized countries in 1982 is given in Table 46.

Almost all companies developing/manufacturing silicon carbide components for heat engine applications are also developing/manufacturing products for non-engine applications. The important manufacturers are listed in Table 47. Products made by these companies are given in Appendix 3.

Silicon carbide parts/components have already gained important wear applications in power plants, aluminum industry, electronics, mining & mineral processing, and iron & steel industry (Figure 29).

TABLE 43

List of U.S. Manufacturers of Silicon Nitride and Sialon Products

COMPANY	Si_3N_4 PRODUCTS
Accuratus Corporation	Specialties
Advanced Refractories Tech.Inc	Ultrafine powders
AiResearch Casting Co	Shapes and composites
Air Products & Chemicals Inc	CVD and CNTD Coatings
American Feldmuhle Corporation	Cutting tools
Arco Chemical Co	Metal matrix composites
Aremco Products Inc	Powders and Shapes
Atomergic Chemetals Corp.	Shapes
AT&T Bell Laboratories	Plasma films
AVCO Corporation	Shapes, Composites (with SiC)
Boride Products Inc	Shapes
Cabot Corporation	Shapes
Cerac Inc	Powders, shapes
Ceradyne Inc	Powders and shapes
Champion Spark Plug Co	Specialties
Chemetal Corporation	CVD
Coors Porcelain Co	Si_3N_4 bonded SiC
Corning Glass Works	Oxynitride glasses
Cummins Engine Co	Engine components
Dow Corning Corpn	Fibres (Development)
Duramic Products Inc.	Refractories, Specialties
Eagle-Picher Industries Inc	Hot pressed shapes
Elkem Metals Company	Powder, Direct nitriding,
Ford Motor Co	Engine components(develop)
Garrett Turbine Engine Co	Engine components)develop)
General Electric Co	Powders, components
Greenleaf Tech.Ceramics	Powders,composites,cutting tools
GTE Laboratories Inc.	Shapes, composites
GTE Products Corporation	Powders, cutting tools, shapes
International Harvestor Corp	Engine components(development)
Iscar Metals Inc.	Cutting tools
I squared R Element Co	Refractories, specialties

TABLE 43 (Cont'd)

COMPANY	Si_3N_4 PRODUCTS
Jupiter Technologies	"Superplastic" shapes
Kyocera International	Powders and shapes
NGK-Locke Inc	Engine components (development)
Norton Company	Powders, shapes, cutting tools, berings
NTK Cutting Tools	Cutting tools
Pennwalt Corporation	Bearings (development)
Plessy Inc	Hot pressed materials
Rockwell International	Composites (development)
SKF Industries Inc	Roller bearings
Sohio Engineered Materials	Si_3N_4bonded SiC Shapes
Sundstrand Corporation	Shapes
Tegal Corporation	CVD Coatings
Texas Instruments	Coatings
Union Carbide Corporation	CVD material
ZYP Coatings	Paintable coatings
	Sialon Products
Kennametal Inc	Cutting tools
Norton Company	Cutting tools
Sandvik Inc	Cutting tools
Sohio Engineered Materials	Shapes (development)
Vesuvius Crucible Co	Custom shapes, powders

TABLE 44

List of European Manufacturers of Silicon Nitride and Sialon Products

Company	Silicon nitride products
France:	
Ceramiques Techniques Desmarquet	Powders; shapes under development
Ceratech	Shapes under development
Ceraver	Shapes
ELF Aquitaine	Powders under development
Lafarge Refractaires SA	Silicon nitride bonded silicon carbide refractories
Rhone-Poulenc SA	Powders and fibres under development
Societe Europeene de Propulsion	Silicon carbide/silicon nitride composites under development
West Germany:	
Annawerk Keramische Betriebe GmbH	Shapes and silicon nitride bonded silicon carbide products
Bayer AG	Semi-finished products
Daimler-Benz AG	Engine components under development
Degussa AG	Engine components under development
Elektroschmelzwerk Kempten GmbH	Powders and shapes including cutting tools
Feldmuehle AG	Cutting tools and other shapes
Hoechst CeramTec AG	Shapes; engine components under development
Krupp Forschung	Shapes and composites under development
Motoren- und Turbinen-Union GmbH	Engine components under development
Siemens AG	Thin films by direct nitridation
SKF Engineering & Research Centre	Bearings under development
SKW Trostberg AG	Ferrosilicon nitride
Hermann C Starck Berlin	Powders by direct nitridation; capacity increased significantly in 1986 from 100 tpa
Volkswagen AG	Engine components under development
Italy:	
Fiat SpA	Powders, cutting tools and engine components under development
Montedison SpA	Powders under development
RIV-SKF	Bearings under development
Netherlands:	
Philips Research Laboratories	Thin films

TABLE 44 (Cont'd)

Company	Silicon nitride products
Sweden:	
ASEA AB	Shapes; engine components under development
KemaNord Industrikemi AB	Up to 50 tpa of powders by direct nitriding
Saab-Scania AB	Engine components under development
Sandvik AB	Cutting tools
Seco Tools	Cutting tools
SKF	Bearings
United Stirling AB	Engine components under development
United Turbine AB	Engine components under development
Volvo Flygmotor AB	Engine components and composites under development
UK:	
Advanced Materials Engineering Ltd	Powders and shapes
AE Developments Ltd	13.5 tpa of shapes by direct nitriding
Cookson Ceramics & Antimony Ltd	Powders
Fairey Tecramics Ltd	Engine components under development
Goodfellow Metals Ltd	Shapes
Johnson Matthey Chemicals	Reagent grade alpha-powders
Morgan Roctec Ltd	Silicon nitride bonded silicon carbide
Ricardo Consulting Engineers	Engine components under development
Rolls Royce Ltd	Engine components under development
Spheric Engineering Ltd	Spheres
TAC Engineering Materials Ltd	Powders and shapes
	Sialon products
France:	
Criceram	Powders under development
West Germany:	
Krupp Forschung	Shapes and composites under development
Sweden:	
Sandvik AB	Cutting tools
UK:	
Cookson Ceramics & Antimony Ltd	Powders
Goodfellow Metals Ltd	Shapes
Lucas Cookson Syalon Ltd	Cutting tools and other shapes

TABLE 45

List of Japanese Manufacturers of Silicon Nitride and Sialon Products

Company	Silicon nitride products
Asahi Glass Company Ltd	Powders and shapes
Asahi Kasei Kogyo	Powders by high frequency induction plasma
Denki Kagaku Kogyo KK	100 tpa capacity for alpha- and beta-powders by direct nitridation
Eagle Industries Company Ltd	Mechanical seals
Hino Motors Ltd	Engine components under development
Hitachi Ltd	Engine components and composites with silicon carbide fibres under development
Hitachi Metals Ltd	Cutting tools
Ibiden Company Ltd	Ferrosilicon nitride by direct nitridation
Ishikawajima-Harima Heavy Industries	Engine components under development
Isuzu Motor Company	Engine components under development
Japan Metals & Chemicals Company Ltd	Shapes by reactive sintering
Japan Pillow Block Manufacturing	Bearings under development
Kawasaki Refractories Company Ltd	Silicon nitride bonded silicon carbide refractories
Kobe Cast Iron Steel Works	Shapes by gas pressure sintering under development
Kobe Steel Ltd	Shapes by HIPing under development
Komatsu Ltd	Engine components under development
Koyo Seiko Company Ltd	Bearings by carbothermal reduction
Kubota Ltd	Powder
Kurosaki Refractories Company Ltd	Silicon nitride-silicon carbide composite; pilot plant for powders
Kyocera Corporation	Powders, engine components, bearings and other shapes
Kyoritsu Yougyo Genriyo	Powders
Mazda Motor Corporation	Engine components under development
Mitsubishi Electric Corporation	Plasma deposited films
Mitsubishi Gas Chemical Company Ltd	High purity powder
Mitsubishi Heavy Industries Ltd	Rotors; other components under development
Mitsubishi Motors Corporation	Engine components under development
Mitsubishi Paper Mills	Whisker sheets
Narumi China Corporation	Powders and shapes
NGK Insulators Ltd	Rotors; other engine components under development
NGK Spark Plug Company Ltd	Rotors and other shapes; other engine components under development
Nihon Cement Company Ltd	Powders
Nippon Carbon Company Ltd	Fibres under development
Nippon Denko KK	140 tpa capacity for powders
Nippon Gaishi Company Ltd	Shapes under development
Nippon Glass Company Ltd	Engine components
Nippon Kagaku Togyo Company Ltd	Powders and grinding media
Nippon Kokan KK	Powders and shapes
Nippon Steel Corporation	Pilot plant for powders

TABLE 45 (Cont'd)

Company	Silicon nitride products
Nippon Telegraph & Telephone Public Corporation	Films by plasma-enhanced CVD
Nippon Tungsten Company Ltd	Powders and shapes including cutting tools
Nissan Motor Company Ltd	Turbochargers and other engine parts
Noritake Company Ltd	Powders and shapes
Onoda Cement Company Ltd	Powders and shapes; 60 tpa planned
Shinagawa Refractories Company Ltd	Shapes under development
Shin-Etsu Chemical Company Ltd	Shapes under development
Showa Denko KK	Powders; shapes under development
Sumitomo Electric Industries Ltd	Powder and composites
Sumitomo Metal Mining Company Ltd	Powders by hybrid CVD technology
Taiyo Chemical Industries Company Ltd	Whisker sheets
Tateho Chemical Industries Company Ltd	Whiskers and composites reinforced with silicon carbide whiskers
Tokyo Kokyu Rozai Company Ltd	Silicon nitride bonded silicon carbide
Toshiba Ceramics Company Ltd	Powders and shapes; engine components under development
Toshiba Tungaloy Company Ltd	Cutting tools
Toyo Soda Manufacturing Company Ltd	Powders; shapes under development
Toyota Motor Corporation	Engine components under development
Ube Industries Ltd	100 tpa capacity for powders; also whiskers
	Sialon products
Hitachi Ltd	Shapes
Hitachi Metals Ltd	Shapes and a 30% titanium nitride composite
Isuzu Motor Company	Engine components under development
Koransha Insulators Ltd	Shapes
Mitsubishi Metals Corporation	Shapes; rotors under development
NGK Spark Plug Company Ltd	Cutting tools; engine components under development
Nippon Kokan KK	Powders and shapes of composite with up to 30% boron nitride
Shinagawa Refractories Company Ltd	Shapes under development
Tateho Chemical Industries Company Ltd	Composites reinforced with silicon carbide whiskers
Tokyo Yogyo Company Ltd	20 tpa capacity for sialon with 10% boron nitride composite

TABLE 46

Estimated Consumption of Silicon Carbide by End-Use for the Western Industrialized Countries in 1982

	% of Total				
	North America	Western Europe	Japan	Other	Total
Abrasives	35	40	15	90	40
Refractories	15	25	70	-ve	30
Metallurgical	45	30	10	-ve	25
Other	5	5	5	10	5
Total	100	100	100	100	100
	000 tonnes				
Abrasives	35	70	10	20	135
Refractories	15	45	40	-ve	100
Metallurgical	45	50	5	-ve	100
Other	5	10	5	5	25
Total	100	175	60	25	360

TABLE 47

List of World Manufacturers of Silicon Carbide Ceramics

COMPANY	COUNTRY
Sohio Engineered Materials	USA
Norton Co	USA
Coors Porcelain	USA
Greenleaf Tech Ceramics	USA
Ceramatech	USA
Kyocera International	USA
Garrett Turbine Engine Co	USA
ESK	W.Germany
Feldmuhle	W.Germany
SIGRI Elektrographit GmbH	W.Germany
Hoechst CeramTec AG	W.Germany
British Nuclear Fuels Ltd	U.K
Morgan Matrock	U.K
Asahi Glass	Japan
Showa Denko	Japan
Hitachi, Ltd	Japan
Hitachi Chemical Co	Japan
Shi-Etsu Chemical Co	Japan
Toshiba Ceramics	Japan
Ibiden Co., Ltd	Japan
NGK Insulators	Japan
Kyocera Corp	Japan
Sumitomo Electric Co	Japan
Nippon Tokusha Togyo KK	Japan
Nippon Rutshio Co., Ltd	Japan
Tateho Chemical Industry	Japan

5.7.2.3 Heat Exchangers

The metallurgical industries used to rely on ceramic brick heat exchangers and regenerators to provide high temperature combustion air for furnace applications. Although serving useful purpose, they were not very efficient, leaked in operation, and were able to withstand only low air pressures. In the late 1930's low-leakage metal recuperators were developed for many high-pressure applications and they gradually replaced ceramic types in many applications.

Metal heat exchangers are suited to handling clean waste gases up to a temperature of 1000 °C and for preheating air up to 550 °C but at higher temperatures and with corrosive atmospheres other materials have to be used.

The wide range of industrial applications for heat exchangers include:

- basic oxygen furnaces
- nickel, zinc and copper refining furnaces
- glass melting furnaces
- forge and billet furnaces
- sulfur ore processing
- copper reverberatory furnaces
- ammonia oxidation
- waste incineration

The candidate materials for ceramic heat exchangers are: silicon carbide, silicon nitride and glass-ceramics. To date, the most frequently used material has been silicon carbide but a recuperator developed by AiResearch Manufacturing Company for the Gas Research Institute utilizes either silicon carbide or silicon nitride. The shell and the heat exchanger contains some 600 tubes each 120 cm long with an outside diameter of 2.5 cm and wall thickness of 0.3 cm. The unit which was expected to cut fuel costs by 50% has been evaluated by Lone Star Steel Company.

Ceramic units have not, however, gained widespread acceptance yet in a market estimated to be about US$ 1 billion, partly because the early demonstration units were not sufficiently rugged and partly because of cost - five times as much as metal units.

The Coors Porcelain Co., has recently developed the technology for making 2.5 cm diameter smooth tubes in large quantities for about US$ 100 per metre as compared with the previous price range of US$ 130 to US$ 500. Sohio Engineered matetials Co., also has developed a high-volume extrusion process that for the first time allows the fabrication of tubes with internal fins and baffles. Because of the increased surface area - up to three times that of smooth tubes - units can be

smaller and thus less expensive.

Developments in Japan include the Nippon Kokan KK reactive sintering process which allows fabrication of silicon nitride parts up to 1 metre in length. These are reported as having high strength and excellent thermal shock resistance up to 1100 °C and thus suitable for heat exchanger tubes. The price in 1982 was in the range US$ 42 to US$ 64 per kg - about one-tenth of that for conventional hot pressed parts. Other useful developments include the continuous pressing process whereby isostatic pressing is combined with extrusion on a continuous cycle basis, and a silicon nitride-silicon carbide composite - Kuroceram - developed by the Kurosaki Refractories Company Ltd.

Potential savings using silicon carbide heat exchangers have been demonstrated. A study undertaken by the AiResearch Manufacturing Company for the Los Alamos National Laboratory on the use of heat pipes for the recovery of heat from the flue gases of high temperature industrial furnaces showed that, using siliconized silicon carbide costing US$ 55 per kg for tube production and US$ 148 per kg for refractory liner, payback periods were less than one year on fuel savings of:

- 43.4% for an aluminum remelt furnace with 980 °C air preheat
- 43.8% for a steel soaking pit with 980 °C air preheat, and
- 57.1% for a glass melting furnace with 1230 °C air preheat

To date silicon carbide has proved to be the preferred material for new generation ceramic heat exchangers. However, silicon nitride is also expected to be used either in conjunction with silicon carbide or alone depending upon application requirement.

6. INTERNATIONAL PERSPECTIVE

Historically, the development of advanced structural ceramics was initiated in the early 1970's in the U.S. followed by W.Germany and Sweden. These activities resulted in a better scientific understanding of the performance of these materials, specifically engineering design criteria governing their use. The international race for the development and commercialization of these materials, however, began in the early 1980's with the realization that Japan had achieved a technological leadership position in a short span of about five years; and that Japan had established a national commitment to gain supremacy in world markets.

In the last five years (1982 -1987), several significant changes have taken place in terms of: (i) technology development; (ii) commercialization; (iii) economic forces; and (iv) relative international leadership position.

The technological problems, particularly reproducibility in manufacture, reliability in service and process costs have proved to be much more difficult to solve than anticipated five years ago. The projected time frame for achieving satisfactory solutions to these problems leading to successful penetration into the heat engine market place has slipped by. Nevertheless, first generation materials have proved to be satisfactory for a number of applications and are providing a breathing space. It is now recognized that the original goal towards an "all ceramic engine" cannot be realized and that the objectives have to change i.e., opportunities for introducing ceramic components into engines should be pursued instead of a complete ceramic engine. Optimism prevails in the international technical community that satisfactory solutions can be found with further research and development.

Commercialization of advanced structural ceramics has taken a different turn compared to five years ago. There is increasing pressure on the companies that have invested in the development of technology to recover R&D costs by commercializing the first generation materials in non-engine markets. This has resulted in a new marketing strategy i.e., to match the wear/erosion/corrosion properties of advanced structural ceramics to meet the needs of other industrial sectors. The successful penetration of advanced ceramic cutting tools is a good example. Other industrial applications in the mining, machinery, chemical & petrochemical, oil & gas, pulp & paper industries are being pursued.

The economic forces that contributed to the original impetus to develop these materials for heat engine applications - high energy costs as a result of the oil embargo of the 1970's, environmental requirements and strategic material considerations - have less impact than before. Now that the use of advanced ceramic components in heat

engines is a reality, and the future is looking bright, interest is turning towards other opportunities. The new combination of forces include: efficiency/productivity gains that can be achieved in other industrial sectors by the use of advanced ceramic coatings and/or components; the need to find markets for the first generation materials to recover R&D investments; and the need to establish and gain new markets.

The relative international leadership position is changing rapidly. Four years ago Japan was the undisputed world leader in advanced structural ceramics. This position, however, has changed in the last two years. U.S. and W.Europe have made significant gains in the development of technology and commercialization of products. The new international forces can be represented as shown in Figure 30. Developments in each country are interacting/pushing the other country: U.S. is reacting to developments in Japan and W.Europe; W.Europe is reacting to developments in Japan and the U.S.; and Japan is reacting to developments in U.S. and W.Europe. Although Japan has some advantages in terms of technology, commercialization and lead time, it no longer is the undisputed leader in the market place. Another factor that is playing an important role against Japan is the high value of the Yen. Because of the high value of the Yen, the economic advantage that Japan has enjoyed to date is not expected to continue. Nevertheless, Japan is, and will be, a dominant economic force.

A brief review of the present international activities follows.

6.1 Japan

According to IBI Inc.,(*) about 200 Japanese companies are estimated to be engaged in the production or research and development of advanced ceramics and fine ceramic powders. Starting with chemical companies in the case of fine ceramic powders, and with porcelain/cement companies in the case of sintered products, Japanese participants in advanced ceramics come from a wide spectrum of industrial sectors including steel, non-ferrous metals, machinery, electronics and textiles. If related products and production equipment are included, the number of companies directly or indirectly participating in the advanced ceramics industry is estimated to be about 300.

However, the number of Japanese companies which are currently participating in markets for advanced ceramics and fine powders on more than just a sample shipment basis is much less - of the order of about 150. Further, production capacities are limited among the majority of these companies, especially for engineering ceramics and

---

(*)"Advanced Ceramics in Japan: Market Trends and Industry Structure,". IBI Inc., Tokyo, March 31, 1987. (Prepared for the Canadian Embassy).

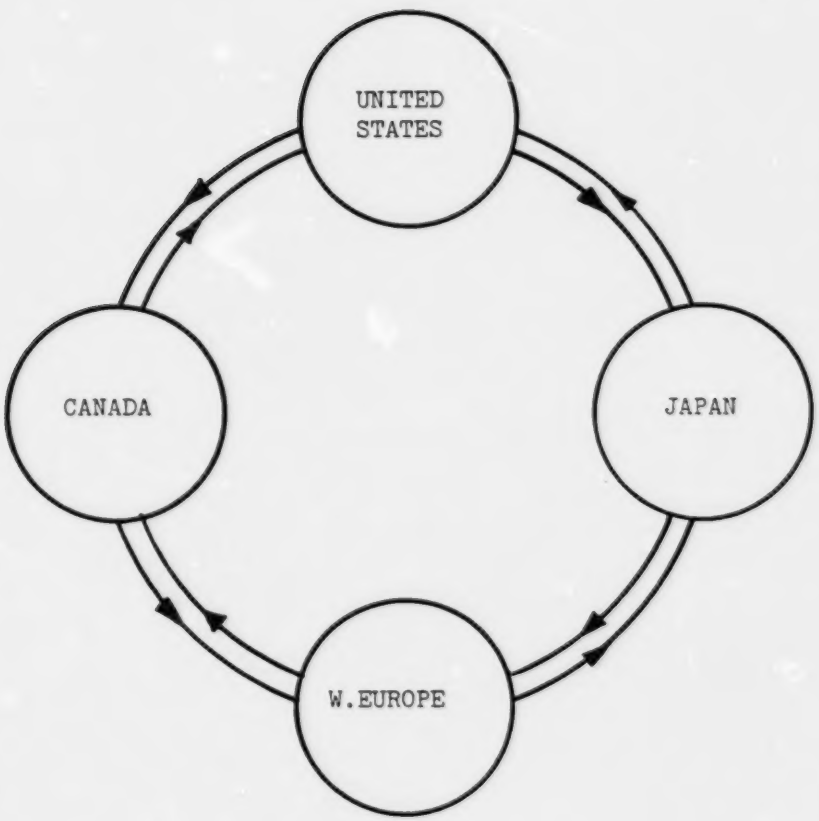


Figure 30. International Forces in Advanced Ceramics

fine powders. The participating sector breakdown for ceramic powders and sintered products is given in Figure 31. Of the 90 companies involved in ceramic powders (76 Japanese + 14 overseas companies), 41% are chemical companies. Most of the chemical companies are large and diversified, including such industry leaders as Ube Industries, Sumitomo Chemicals, Showa Denko and Toyo Soda. A number of smaller, privately held Japanese chemical companies are also producing or developing ceramic powders, including Daimei Kagaku Kogyo and Kojundo Chemical Laboratories.

Porcelain/cement companies are next most numerous group of fine ceramic powder supliers in Japan - accounting for 20%, or 24% if overseas companies are excluded. In contrast with chemical companies, many of these companies are reported to be still in the R&D stage or sample shipment stage.

Overseas companies active in supplying ceramic powders to Japanese users include: Dupont, Union Carbide, Corning, Alcoa, and Advanced Refractory Technologies of U.S.; Rhone-Poulenc of France; Hoechst and Herman C.Starck of W.Germany; and Lonza of Switzerland. DuPont, Corning, Alcoa, Hoechst, H.C.Starck and Rhone-Poulenc sell directly through Japanese subsidiaries and representative offices, while the other companies are represented by trading companies or other Japanese companies.

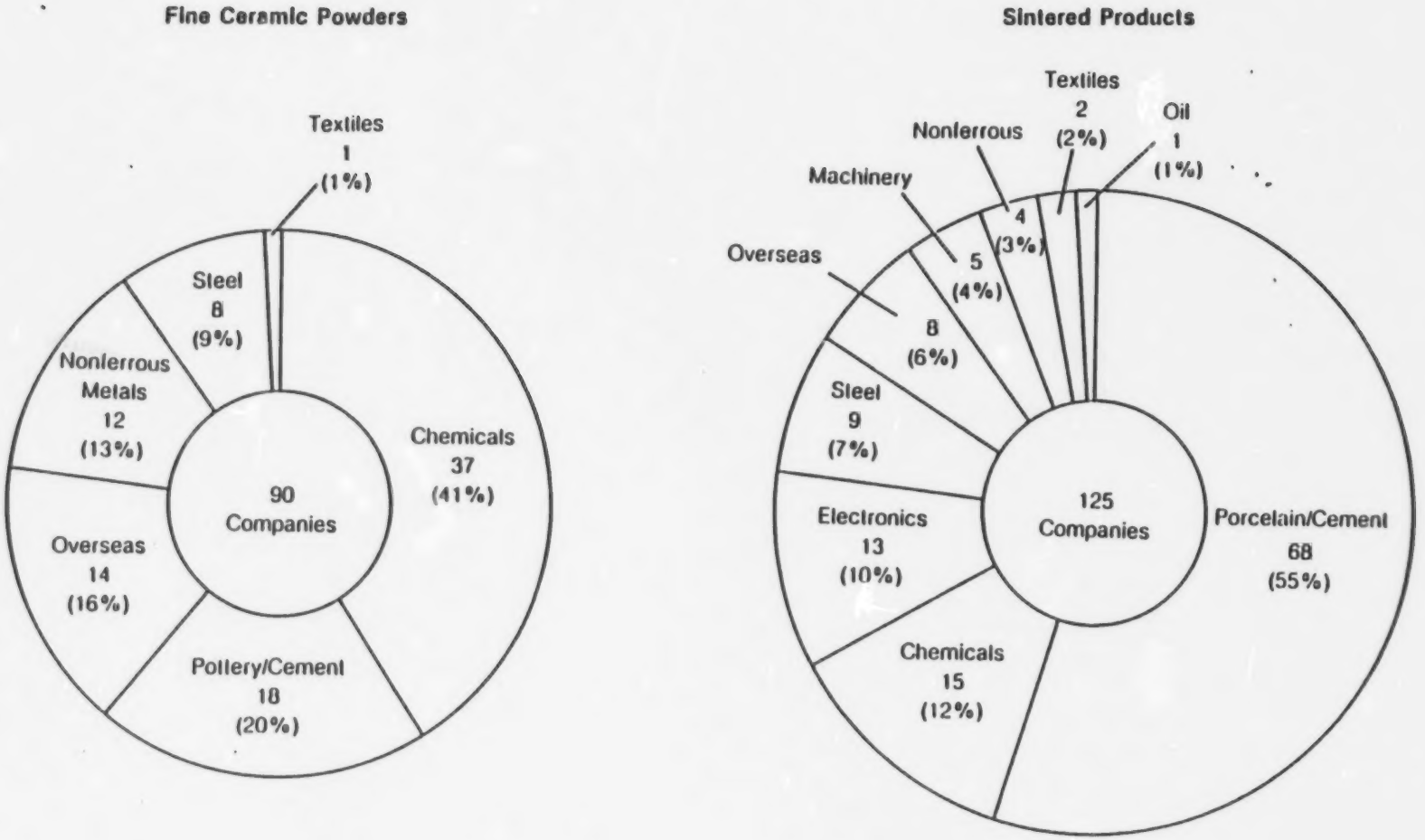
About half of the Japanese companies producing or developing advanced ceramic component products (68 out of 125) come from porcelain/cement industry sector. Leading companies include: Kyocera, Asahi Glass, NGK Spark Plug, NGK Insulators, Toshiba Ceramics, Narumi China, Ibiden, Nihon Cement, Toto and Shingawa Refractories. A large number of smaller, privately held pottery and ceramic producers are also active.

Other sector companies active in sintered product production and development include leading companies from the chemical, electronic and steel industries.

Oveseas companies supplying advanced ceramic products to Japan include: Corning, Union Carbide and Brush Wellman (USA); Hoechst (W.Germany); and Lucas Cookson Syalon.

Both the Ministry of International Trade and Industry (MITI) and Japanese industry continue to believe in the long-term success of their industrial strategy for the 1990's. Some of the important recent developments are:

- Continued interest of MITI in promoting/supporting Advanced Ceramics such as: creation of the Japan Fine Ceramics Center (JFCC) in Nagoya; accelerating in-house R&D in MITI-controlled



Source: *Nikkei New Materials, November 3, 1986.*

Figure 31. Breakdown of Advanced Ceramics Industry in Japan by Sectors

laboratories; revising the statistical data collection system for advanced ceramics with a view to monitor the progress more accurately; and improvements in taxation system to assist in the development and promotion of basic technology and research.

- Continued funding of industry projects on advanced ceramics as a part of Japan's 10-year national program on advanced materials.

- Commitment of Japanese industry, through the Japan Fine Ceramics Association (JFCA), to promote the development of advanced ceramics.

Published reports indicate that interest in the development of "all ceramic engines" has waned. Only Isuzu appears to be committed to this objective; it hopes to market small trucks equipped with all-ceramic-engines by 1990. All the other manufacturers are continuing their efforts/commitments to develop and introduce new components in addition to the already commercialized parts such as turbochargers, glow plugs, swirl chambers etc. As far as the gas turbine engine is concerned, MITI has initiated a 8-year program (cost Yen 20 billion) to develop ceramic gas turbine engines. Industrial participants are Nissan, Toyota and Mitsubishi supported by Japanese ceramic manufacturers. The plans are to develop two engines, one for cars and the other for trucks. The engines are to be designed for operation at 1350 C.

Because of the delay/uncertainties associated with the commercialization of advanced ceramics for engines, there is increasing pressure to develop uses in other industrial sectors. Efforts to incorporate advanced ceramic components for abrasion/wear and heat/corrosion applications are increasing. These efforts are being introduced at the design stage.

From an international perspective, Japanese industry appears to be going towards joint-ventures and technology-transfer - particularly in the U.S. Japanese companies are also entering into technology-transfer with foreign firms to take advantage of new developments e.g., ASEA HIP technology.

6.2 United States

Both the U.S. government and industry have reacted and responded positively to counteract the perceived threat from Japan. The U.S. position just a few years ago has been described by Westwood(*) as follows: ".. U.S. industry and government seemed to see themselves as

---

(*) "Advanced Ceramics - Opportunity and Challenge,". A.R.C.Westwood and Jan P. Skalny. Adv.Cer.Mat. Vol 1, No 1, P21 (1986)

adversaries rather than allies, and university engineering departments were wasting away, underfunded, poorly equipped, and out of touch". Speaking of recent developments Westwood concludes: " Enthusiasm has also been growing recently in the U.S., especially during the past two years. And although it does not yet rival Japan's "fever," the situation fortunately is a far cry from that of just a few years ago - when our ability to put together an effective equivalent to the cooperative and focused efforts of Japan's MITI-catalyzed government and industry consortia was in real doubt."

Both the Federal and State governments have taken initiatives to encourage and support research, development and commercialization of advanced ceramics. The federal government initiatives are:

- Increase in activities in federal government laboratories;
- Increase in federal support of engineering research in universities;
- A new spirit of cooperation between federal agencies and industry;
- Support for mission-oriented programs to develop advanced ceramics through Departments of Defence, Energy and Transportation.

Ceramics R&D activities in the federal government laboratories has increased substantially. The principal laboratories performing ceramic research are listed in Table 48. The National Bureau of Standards has implementd a $10 million/year program recently. Also, a National Centre for assisting the advanced structural ceramics industry has been set up in the Oak Ridge National Laboratory at a cost of US$ 19 million. The total federal expenditures on ceramics research, not including the above, is estimated at US$ 47 million for fiscal year 1987(Table 49).

Federal support for engineering research in the universities has also begun to increase substantially with the establishment by the National Science Foundation of several multidisciplinary engineering centers e.g., the Center for Ceramics Research at Rutgers University, the Center for Dielectric Research at Penn State, the Ceramics Processing Center at MIT.

A new spirit of cooperation between federal agencies and industry is also arising. Federal laboratories, such as Oak Ridge National Laboratory and Sandia National Laboratory, now have technology transfer functions active and in place. Cooperative programs are increasing in number, especially projects involving shared use of expensive apparatus and facilities. Industrial support of promising work by scientists

TABLE 48

Principal U.S. Federal Government Laboratories Performing Advanced Ceramics Research and Development

AGENCY	LABORATORY
Department of Defence	Air Force Materials Laboratory, Dayton, Ohio
	Army Materials Technology Laboratory, Watrertown, Mass
	Naval Research Laboratory, Washington, D.C.
Department of Energy	Ames Laboratory, Iowa State University, Ames, Iowa
	University of Illinois Materials Research Laboratory, Urbana, Illinois.
	Argonne National Laboratory Argonne, Illinois.
	Lawrence Broccoli Laboratory Pasadena, California
	Los Alamos National Laboratory Los Alamos, New Mexico
	Oak Ridge National Laboratory Oak Ridge, Tennese.
	Pacific Northwest Laboratory Richmond, Washington
	Sandia National Laboratory Albuquerque, New Mexico

TABLE 48 (Cont'd)

Principal U.S. Federal Government Laboratories Performing Advanced Ceramics Research and Development

AGENCY	LABORATORY
National Aeronautics & Space Administration	Lewis Research Center Cleveland, Ohio
	Langley Research Center Hampton Roads, Virginia
	John Buckley Ames Research Center Moffett Field, California
Department of Commerce	National Bureau of Standards Gaithersberg, Maryland.
Department of Interior	Bureau of Mines Washington, D.C.

TABLE 49

U.S. Federal Government Programs on Advanced Structural Ceramics

	FY 1983	FY 1984	FY 1985	FY 1986	Estimated FY 1987
Department of Energy:					
Conservation and renewable energy:					
Vehicle propulsion	11.4	12.7	11.9	10.0	5.2
Advanced materials	3.2	5.1	6.0	8.7	6.5
Industrial programs	1.0	2.3	1.7	1.5	0.8
Energy utilization research	0.5	1.5	1.8	1.8	1.0
Fossil energy:					
Advanced research and technology development	1.0	1.1	1.5	1.2	0.9
Energy research:					
Basic energy science	3.0	4.4	4.6	4.5	4.5
NASA:					
Lewis Research Center	3.0	2.5	5.4	4.5[a]	4.6[a]
National Science Foundation	2.9	3.3	3.6	3.6	3.7
National Bureau of Standards				2.2	3.0
Department of Defense:					
Defense ARPA	7.7	8.2	9.4	10.0	5.0
U.S. Air Force	3.0	3.4	4.7	4.7	5.0
U.S. Army	4.7	6.0	2.5	4.4[b]	4.7[b]
U.S. Navy	1.2	1.3	1.4	2.3	2.3
Total	42.6	51.8	54.5	59.4	47.2

[a]Includes $1.8 for Manpower Salaries.
[b]Includes $4.0 for TACOM Diesel.

SOURCE: Robert B. Schulz, Department of Energy.

working in government laboratories is beginning to occur. Very recently, the U.S. Commerce Department has been actively involved in assisting industry to set up Ceramics Advanced Manufacturing Development and Engineering Center (CAMDEC) to develop cost-effective reliable processing techniques and manufacturing technology for the commercialization of structural ceramics. CAMDEC is an industrially sponsored and managed consortium with access to the national laboratories like Oak Ridge. The U.S. Commerce Department is also assisting in the setting up of an Advanced Ceramics and Composite Program (ACCP), an R&D partnership between industry, universities and government at the Midwest Technology Develoment Institute (MTDI). MTDI is a non-profit organization created in 1985 by the governors of the states of Illinois, Indiana, Kansas, Michigan, Minnesota, Nebraska, North Dakota, Ohio and Wisconsin. It is located in St Paul, Minnesota.

The State of New Jersey has funded the Rutgers University to build facilities for the Center for Ceramics Research, originally created by funding from NSF. Similarly, the State of New York is assisting Alfred University in setting up an Advanced Technology Center.

Mission-oriented programs are supported by various federal departments, chiefly the Departments of Defence, Energy and Transportation. The programs supported by the Department of Defence through the various services are confidential, particularly those related to the Strategic Defence Initiative (SDI). The Department of Energy is continuing to fund the development of all-ceramic gas turbine engines. The AGT 101 program at Garrett is being funded for a period of 5 years at a total cost of US$ 32 million of which DOE is funding US$ 25 million. The development of efficient diesel engines is also being supported with federal funds.

That advanced ceramics in the U.S. is receiving support and attention is reflected by the statistics on the attendance and number of papers presented at the Annual Meeting of the American Ceramic Society listed below:

Year	Attendance	No.of Papers
1981	3,850	750
1982	3,670	760
1983	3,690	890
1984	5,170	1,100
1985	5,700	1,035
1986	5,600	1,100
1987	7,400	1,180

The majority of papers are from universities indicating the increase in ceramic research at universities.

Perhaps the most noteworthy and noticeable developments are the initiatives taken by industry. Some of the important initiatives are:

- Industry support to academic research and formation of industry-university consortia.
- Entry of non-ceramic companies into the field of advanced ceramics.
- Formation of joint-ventures by industry.
- Formation of United States Ceramic Association (USACA).

Industry support for academic research has increased markedly and continues to increase. The early initiatives were the Center for Ceramic Research at Rutgers, Ceramic Processing Consortium at MIT, and the Center for Dielectric Studies at the Pennsylvania State University. Each of these centers has more than 25 industrial members. Recently, the number of these industry-university centers has grown considerably and some of the new centers are at the New York State College of Ceramics, Case Western Reserve, Missouri School of Mines, Clemson College and Ohio State University.

Another important development is the entry of traditionally non-ceramics companies into the field of advanced ceramics. Most of the new comers have done so either by internally generated capability and/or acquisition of ceramic companies. Some of the important examples are: IBM, Dupont, W.R.Grace, Allied-Signal, Standard Oil, DuPont, AVX, Borg Warner, Cabot, Dow Chemical, Elkem Metals, General Electric and Air Products & Chemicals. Ceramic Industry magazine identifies 96 companies active in advanced ceramics.

According to a recent survey(*), 23 U.S. advanced ceramics companies spent a total of US$ 153 million in R&D, i.e., an average of $6.6 million proving that the companies believe in the long term viability of this technology. These companies received $46.3 million of federal funding for advanced ceramics. The survey also revealed: (i) in 1986, R&D expenditures for advanced ceramics totalled 23% of sales and was expected to go up to 25% of sales in 1987; (ii) nearly 33% of the respondents indicated that they would boost professional R&D staff levels in 1987.

Some advanced ceramics manufacturers have entered into partnership with auto parts manufacturers to develop and commercialize components for automobile applications. There are two reasons behind

---

(*) Study released by the United States Advanced Ceramics Association in December 1987. (Ref: Ceramic Industry, January 1988, Page 10).

this development. Firstly, the big American auto manufacturers initiated a new policy in 1982 requiring the auto parts manufacturers to assume more responsibility for R&D. This automatically required some of the auto parts manufacturers (particularly engine component manufacturers) to address the development of ceramic components. In order to reduce risks and lead times involved, some of the parts manufacturers have formed joint ventures with well known ceramics manufacturers with background in advanced ceramics. Some of the important examples are:

Auto Parts Manufacturer	Ceramics Manufacturer
TRW	Norton Co (#)
Eaton Corp	GTE Corp
Ford (*)	Ceradyne

A new technology called "Lanxide Technology" to manufacture advanced ceramic components appears to be gaining momentum. The technology was developed by Lanxide Corporation in the U.S.. Alcan Aluminum Ltd., has participated in this development with equity participation. It is understood that significant progress has been made in the development of this technology and many components made by this technology are being evaluated by auto manufacturers. A new company called "Alanx" has been formed between Lanxide Corporation and Alcan Aluminum Ltd., in Delaware, U.S., to manufacture these components. Dupont and Lanxide have entered into a separate agreement to jointly develop and manufacture advanced composites using Lanxide technology.

The commercialization of energy efficient diesel engines containing advanced ceramic components/coatings is expected in the next few years. Companies such as Cummins Engine, Deers, Caterpillar are actively participating in this activity.

That the U.S. industry has taken seriously the threat posed by Japanese leadership to date in advanced ceramics is demonstrated by the formation of the United States Advanced Ceramics Association (USACA) which has a membership of 35 companies. Membership of USACA is listed in Table 50 which indicates that the interest in advanced ceramics is not restricted to ceramics and auto manufacturers. In fact, the general feeling is that the near term potential for advanced ceramics is in the non-engine industrial applications. Engine market is expected to develop and grow, but at a slower pace than originally anticipated.

(*) Ford has teamed up with Ceradyne in a joint venture by transferring all the technology developed in-house.

(#) Silicon nitride valves made by Norton/TRW Ceramics are being road tested in a 1988 Oldsmobile Cutlas Ciera and have logged more than 5000 miles.

TABLE 50

Members of the U.S. Advanced Ceramics Industry Association

1. Coors Limited
2. Advanced Refractories Technology Inc
3. Alcoa
4. Champion Sparkplug
5. Chrysler Corporation
6. Corhart Refractories
7. Corning Glass
8. Dow Chemical Co
9. Dow Corning
10. Ferro Corporation
11. Garrett Corporation
12. Dupont
13. General Ceramics
14. General Motors
15. GTE Corporation
16. Lanxide Corporation
17. Martin Marietta Corporation
18. McDanel Refractories
19. Norton Co
20. Sohio Engineered Materials Co
21. Titan
22. Union Carbide
23. W.R.Grace Co

6.3 France

France, like other W.European countries has increased its national effort on the development and commercialization of advanced ceramics, both powders and products.

The total R&D expenditure in France on all subjects was 90 million francs (US$ 13 million) corresponding to 300,000 employees. It represents a little more than 2% of GNP. The support from the government was at the level of 54 billion francs (US$ 8 billion) including financing such agencies as Centre National de la Researche Scientifique (CNRS) and Commissariat a l'Energie Atomique (CEA). The CNRS covers almost all fields of science and has a staff of 25,000 with about 10,000 scientists with a budget of 8 billion francs. The CEA is oriented toward research and development of nuclear technologies and has about 15,000 staff with a budget of 13 billion francs.

The major centers involved in research and/or education in materials science belong to such large organizations as universities, engineering schools and CNRS. The system of scientific classification in use in France does not recognize materials science. It is part of many disciplines e.g., physics of condensed matter, chemistry of solids, and mechanics. However, during the past few years, the importance of research on materials has led several institutions to set up specific structures e.g., CNRS/Programmme Interdisciplinaire de Researche sur les Materiaux.

Similar structures have been established in various government agencies. This includes the Department Materiaux of the Mission Scientifique et Technique (MST) of the Ministre de la Researche et de la Technologie (MRT). The expenditures on ceramics in 1985 were as follows:

Agency	Ceramics & Electronic Materials	Total Expenditure on Materials
CEA	85 million francs	500 million francs
Defence	60 "	358 "
MST/MRT	47 "	145 "
Others	50 "	100 "

A five year materials program called "Programme Mobilisateur Materiaux", also known as I-D-IMAT was launched in 1986 which includes ceramics.

French industry and government became interested in engineering ceramics in 1974. Advanced ceramics in France were then limited to alumina wear parts and some electronic ceramics (capacitors, ferrites, high voltage devices, piezoelectrics etc.).

Military applications of advanced ceramic materials such as radomes, armor platings, and infrared optics have received extensive R&D support. The company Ceramiques Techniques Desmarquest continues to be a main supplier of these products.

The main industrial companies concerned with the manufacture of engineering ceramics are listed in Table 51.

Ceraver once had more than 1,600 people working on technical ceramics of which 1,000 worked on porous alumina diffusion barriers for nuclear program. The latter program ended in 1980 and work is now limited to biomaterials and porous membranes for ultrafiltration.

Ceramiques et Composites was born when Rhone-Poulenc took over the Ceraver R&D Department and the technology of manufacturing silicon based ceramics. This company has the advantage in that the large chemical group of Rhone-Poulenc develops ceramic powders, rare earth oxides and silicon based compounds and can work closely with the ceramic group. Aerospatiale has a share in this venture. A turnover of about 100 million francs is planned for the near future.

Ceramiques Techniques Desmarquest was independent until the mid-1970's when it became a subsidiary of Lafarge group. In 1985, it was taken over by Pechiney. Alumina parts are the major products of the Evreux plant, with spray nozzles and wear parts being the most important ones. Other products include: zirconia oxygen sensors, and military products. Active R&D is in progress on TZP, silicon nitride and composites.

Compagnie Industrielle des Ceramiques Electroniques (CICE) was a division of Thomson group until 1984. Now, like Isolantire, they are a subsidiary of Stettner. Their main products are wear parts and alumina substrates.

The total shipment of French engineering ceramics in 1985 was around 40 million francs, excluding electronic ceramics and ceramic powders. The major suppliers of chemicals and raw materials for the advanced ceramic industry, and their respective products are:

Company	Materials supplied
Rhone-Poulenc	Rare earths, Al_2O_3, Y_2O_3, ZrO_2, & SiO_2
Pechiney	Al_2O_3, ZrO_2, and SiC
Baikowski	Pure Al_2O_3
SEPR	Zircon and ZrO_2

It is interesting to note that both Rhone-Poulenc and Pechiney have vertically integrated businesses as in other countries with large chemical groups.

TABLE 51

Overview of French Activity in High Performance Ceramics

Industry	Materials	Products	Personnel	Turnover (million francs)	
				Current	Projected
Ceraver*	Al_2O_3	Hip joints, porous membranes, translucent tubes, metalizing, armor plating	260	80	100
Ceramiques et Composites'	SiC Sialon Cordierite Mullite	Wear parts, thermal insulation	50[1]		100
Ceramiques Techniques Desmarquest[1]	Al_2O_3 PSZ, TZP SiO_2	Nozzles, oxygen sensors, radomes, armor	160	60	
CICE'	Al_2O_3 TiO_2	Wear parts, thread guides, substrates	210	70	
Isolantite	Steatite Al_2O_3		80	20	
Quartz et Silice**	B_4C, PZT		50		

*Located at Tarbes; subsidiary of Compagnie Generale d'Electricité. 'Located at Tarbes; subsidiary of Rhone Poulenc. [1]Personnel projected to total 100. [1]Located at Evreux and Trappes; subsidiary of Pechiney. 'Located at Montreuil. **Division of St. Gobain.

France also has a large R&D effort on the development and commercialization of advanced ceramics for automotive engines. These activities are summarized in Table 52. Coordinated and cost-shared programs have been initiated by engine makers in cooperation with ceramics manufacturers and research institutions. Components that are being developed include: precombustion chambers, head plates, piston caps, port liners, and rocker arm pads made of TZP, sialon, sintered silicon nitride and composites. Alumina seal rings made by Desmarquest are used in water pumps for Peugeot automotive engines.

Advanced ceramics research programs at French institutes and universities are listed in Table 53. The need for focusing the research potential of large institutions such as CEA and CNRS universities on items as critical as advanced ceramics is becoming accepted by all partners. EEC programs such as EUREKA, Heavy Element and Radioactive Material Electromagnetic Separator, Bright RADAR Indicator-Tower Equipment, and EURAM are expected to provide the French ceramic community with opportunities to participate in the growing need for advanced ceramics for these projects.

The French national center for ceramics is located at Limoges. The center is built around the Faculty of Sciences of the University of Limoges and the Ecole Nationale Superieure de Ceramique Industrielle (ENSCI). These institutions separately educate students, but work together for research activities. The research activities of the university and ENSCI are coordinated in a laboratory which is named "Ceramiques Nouvelles" or "New Ceramics". This laboratory is under the control of the Centre National de la Researche Scientifique (the French Agency for Public Research). This laboratory employs 50 permanent staff members with about 20 doctorate students.

For additional information on advanced ceramics activities in France, the reader is referred to the following papers:

"Overview of Research on Ceramics in France". J. Casting and B. Escaig
Bul.Am.Ceram.Soc., Vol 65, No 9, p 1250 (1986).

"Engineering Ceramics Activity in France,". D. Broussaud
Bul.Am.Ceram.Soc., Vol 65, No 9, pp 1251-1253 (1986)

"French National Center for Ceramics at Limoges,". P. Boch
Bul.Am.Ceram.Soc., Vol 65, No 9, p 1256 (1986).

TABLE 52

Automotive-Related and Other Advanced Ceramics R&D in France

Company	Material	Application
Ceramiques et Composites	SiC, sialon	Heat exchangers, turbine parts, piston engine parts, bearings, cutting tools, furnace fans, filtration equipment
Desmarquest	Y-TZP, SiO_2-based composites, sintered Si_3N_4	Piston engine parts, insulation, tooling, radomes
Aerospatiale	Composites (long and short fibers of SiC, SiO_2 with SiO_2 matrix)	Engine parts, insulation, nozzles
SEP	Composites (long fibers of SiC, Al_2O_3 with SiC, Al_2O_3 matrices)	Engine parts, nozzles
Renault		Engine parts (cars and trucks)
Peugot S.A.		Engine parts (cars only)
SEMT		Ceramics for large piston engines
SNECMA		Ceramics for aircraft turbine stationary parts and for prescision casting
Turbomeca		Ceramics for aircraft turbine stationary parts (vanes, rings, etc.) and ceramic composites for rotors
CGE R&D		Ceramics for engines, solid-state diffusion bonding, solid electrolytes, acoustic microscopy
Rhone-Poulenc	ZrO_2, Si_3N_4 powders	
Criceram	ZrO_2 powders	
Atochem	Si_3N_4, AlN powders	

TABLE 53

Advanced Ceramic Research at French Institutes and Universities

Facility	Major ceramic research areas
ONERA	Ceramic composites, CVD coatings, gas turbine design and component testing
CEA	Ceramics for nuclear applications, powders, hot isostatic pressing, plasma spraying
CNRS and Universities	
Paris-Meudon	Diffusion and creep (Al_2O_3, SiC, etc.)
Orléans	Sintering and properties of ZrO_2
Bordeaux	Ceramic composites
Caen	Mechanical properties and stereology
INSA Lyon	Mechanical properties and stereology, reinforcement of ceramics (second phase dispersion, fibers, etc.), wear
Ecole Centrale Lyon	Ceramic-metal interfaces, wear
Ecole des Mines, St. Etienne	Sintering, hot pressing, second phase dispersion
Limoges	Nitrogen ceramics, sintering, processing, plasma spraying, ceramic precursors

6.4 W.Germany

W.Germany initiated its first national program on advanced structural ceramics in 1974 and completed it in 1983. Ceramic powder manufacturers, ceramic component manufacturers, automobile manufacturers, universities and research institutes participated in this program and significant achievements were made.

A new 10-year national program on advanced materials was initiated in 1985. The areas covered are: ceramics, composites, powder metallurgy and other high temperature materials. Some of the participants in the first national program did not join the new program (Degussa) but many new companies have joined (Hoechst, Bayer).

The ceramic powder manufacturers, particularly H.C.Starck have made significant progress in terms of commercizlization of advanced ceramic powders e.g., H.C.Starck have doubled their silicon nitride production capacity from about 60 tons/year to 120 tons/year. Feldmuhle has increased its product lines in cutting tools; ESK has expanded its product lines as well as market penetration. Perhaps the most noteworthy feature is the fact that Hoechst has expanded its overall involvement in advanced ceramics by business tie-up with SIGRI, ESK and Rosenthall. Together, they form the biggest group in the manufacture of advanced structural ceramics.

As far as the use of advanced ceramics in engines are concerned, Volkswagen is continuing its efforts. The company has no plans to manufacture ceramics but plans to use them only where there is a cost and/or performance advantage. They are continuing their work on the evaluation of ceramics, especially zirconia and aluminum titanate for diesel engines. They have discontinued their earlier program on gas turbine engine development, however, are following the work in the U.S. and Japan very closely. Their current work in ceramics can be described as use of the materials for protection against temperature, corrosion and wear in order to produce more durable or efficient engines. They consider increase in service life as important as an increase in performance. Mercedes Benz are reported to be continuing their work on gas turbine engines but details are not available.

Ceramic engineering education in W.Germany is well established. The universities and polytechnic/technical colleges offering ceramic engineering education are listed in Table 54.

Another important organization doing R&D on advanced ceramics is the Deutsche Forschungsund Versuchsanstalt fur Luft und Raumfahrt (DFVLR). DFVLR obtains 75% of its funds from the government and 25% from industry and the programs are designed toward technology development and transfer in the areas of production, quality improvement- particularly for aerospace applications.

TABLE 54

Ceramic Engineering in 1984 in the Federal Republic of Germany

University/ technical college	Number of professors	Number of students	Graduates	Glass teaching	Ceramics act.	Cements	Graduate students
Universities:							
1. Aachen	4	87	8	1	1	1	24
2. Berlin	3	50	5	1	1	1	15
3. Clausthal	5	130	12	1	1	1	24
4. Erlangen	3	130	12	1	1	0.5	12
Polytechnics/technical colleges:							
1. Duisburg	3	38	8	1	1	0	
2. Hohr-Grenzhausen	6	190	40	1	4	0.8	
3. Nurnberg	5	167	30	1	1	0.3	
Total	29	792	115				75

6.5 United Kingdom

Two industrial organizations, supported by government funds, are developing and commercializing ceramic components for engines. One of them is the "Rolls Royce Club", a consortium of 10 companies involved in the development of gas turbine engines. The original program was for the period 1985-1988. Details of achievements and future plans are not available.

The Consortium for Ceramic Applications in Reciprocating Engines, also known as the "CARE Club", consists of about 32 companies including car, auto parts and ceramics manufacturers. Details of achievements and future plans are not available, however, it is known that R&D is being carried out at the British Ceramics Research Ltd., British Nuclear Fuels Ltd., and UK Atomic Energy Ltd., at Harwell supporting the objectives of the industrial members.

Harwell is known to have enlarged their plasma coating facilities to support R&D work related to the development of wear coatings for auto and other appplications. Morgan Matroc is the biggest company in the U.K. involved in the development of advanced ceramics.

6.6 EEC

EEC is supporting the development of advanced ceramics for a number of years. Its new initiatives designed to accelerate the transition from old industries to new high technology industries are expected to give additional impetus to this effort. Funds are being provided by the EEC, on a 50:50 basis, to participating companies, universities and research institutes for precompetitive research, similar to the MITI programs in Japan. The programs are:

.ESPRIT - The European Strategic Program for Research in Information Technology. The total budget is US$ 2.4 billion to the year 1991, matched equally by industry. (launched in 1983 but continuing)

.RACE - Research and Development in Advanced Communication Technologies for Europe. Launched in 1985, this program provides 50% funds for research in industry and universities.

.BRITE - Basic Research in Industrial Technologies for Europe. This program provides 50% funds for research into new production techniques.

.EUREKA - Created in 1985 to provide assistance to EEC companies to target products, processes and services, a program set up in response to the SDI program of the U.S.

7. STATUS OF ADVANCED CERAMICS IN CANADA

7.1 Overview

The status of "Advanced Ceramics" in Canada was reviewed by the Department of Regional Industrial Expansion, Ottawa, in its Report No.3/86(*). The report reviewed, from an international perspective, the opportunities and threats facing Canadian industry in advanced ceramics. From a Canadian perspective the report made two important contributions. Firstly, it focused attention on the economic benefits of developing and using advanced ceramics to Canadian industry. Secondly, and more importantly, it helped to sensitize industry, governments, universities and other research institutions to the importance of advanced ceramics and its role as an "enabling technology" in assisting/promoting other high technology industries. As a result, a number of new initiatives have resulted in Canada, by industry, by governments and by universities and research institutions. The future looks bright, indeed. The scope of the Canadian advanced ceramic industry as well as the new initiatives that have taken place will be discussed.

Advanced ceramics industry in Canada, although relatively small, is active in the manufacture of a number of products and R&D is aimed towards the development of new products and processes. These activities comprise all the four important areas: advanced ceramic powders, advanced functional ceramics, advanced structural ceramics and advanced ceramic coatings.

Manufacture of ceramic powders is a well established commercial activity in Canada. Alumina powders for the ceramic industry, specialty iron oxides for the ferrite industry and hard metal carbides for the cutting tool industry have been produced for many decades. New products are being developed by both the existing manufacturers and new companies entering the field. To the former category belong reactive aluminas, non-oxide powders such as silicon nitride and aluminum nitride and whiskers. To the latter category belong beta-silicon carbide powder, aluminum nitride, boron nitride and specialty powders based on titanium diboride for plasma coatings applications. Availability of abundant inexpensive energy resources as well as the required raw materials are expected to have positive impact on growth.

In advanced functional ceramics, Canadian companies have specialized in piezoelectrics, both in the component form and as systems, e.g., transducers and sensors. One large international company specializes in capacitors. New industrial activities include the manufacture of sapphire and optoelectronic materials.

(*) "Advanced Ceramics,". Report No.3/86. Office of Industrial Innovation, Department of Regional Industrial Expansion, Ottawa.

Many technical ceramics manufacturers are using their considerable technical and marketing skills to diversify their product lines to include advanced structural ceramic products. Bulk of these new products are oxide ceramics such as alumina, cordierite, zirconia, zircon and silicates. However, R&D is in progress in these companies to develop and commercialize other products. The newer companies tend to concentrate on transformation toughened oxide ceramics, non-oxide ceramics such as boron nitride, silicon carbide, silicon nitride, titanium diboride, ceramic-ceramic composites and ceramic-metal joining.

Well established industrial facilities exist for the deposition of advanced ceramic coatings using thermal and plasma techniques. Many aerospace companies have in-house facilities to service their requirements. Commercial coating facilities service a wide range of requirements ranging from supply/repair of aircraft components to the needs of many industrial sectors for abrasion/wear/corrosion resistant coatings, e.g., pulp & paper, chemical and petrochemical, mining, oil and gas drilling, and machinery. Industrial interest in plasma coating technology is growing resulting in the expansion of activities in existing companies and creation of new enterprises.

Information generated in this study indicates that Canadian industry is addressing the opportunities provided by advanced ceramics from both technological and business points of view. The manufacturers of advanced ceramic products are addressing new products to meet domestic needs as well as for export and significant growth is expected. More importantly, the user sectors, e.g., mining and mineral beneficiation, oil & gas drilling, pulp & paper, machinery and metal working, chemical and petrochemical, are showing increasing interest in using advanced ceramics to improve efficiency/productivity in their operations.

Canada has a significant heritage in the field of R&D in ceramics as reflected by the fact that approximately 10% of the research papers in the Journal of the American Ceramic Society in the last 10 years have been by Canadian scientists. This "science and technology" culture is expected to play an important role in the growth of advanced ceramics in Canada in the coming decades.

Extensive R&D capabilities and facilities in advanced ceramics, both functional and structural ceramics, available in Canadian universities, federal government laboratories and Provincial Research Organizations complement and support industry efforts to meet growing domestic needs as well as to increase exports.

Twelve Canadian universities are active in advanced ceramics research and development, in addition to providing education at undergraduate and graduate level. Support for university R&D comes both

from industry and government departments/agencies. Many of the university professors have well-established international reputations.

Federal government laboratories boast a wealth of expertise and facilities in advanced ceramics and related industrial technologies. In addition to performing their own mandated research, cooperative R&D programs are carried out with industry and universities. The recent initiative of the National Research Council to establish a Coordinator for advanced ceramics activities as part of an effort to promote the development and commercialization of advanced industrial materials in Canada is a welcome development.

Four Provincial Research Organizations have established R&D capabilities in advanced ceramics and carry out research and development programs. In addition, they provide technical assistance to industry, on a contract basis, to develop new products/processes and to improve efficiency/productivity of operations.

The increased interest shown by Canadian industry to participate in the growing field of advanced ceramics is reflected by the formation of new national associations supplementing the 85-year old Canadian Ceramic Society: the Advanced Materials Technology Unit at Queens University; the Canadian University-Industry Council on Advanced Ceramics; the Canadian Advanced Industrial Materials Forum; and the Ontario Center for Materials Research.

Finally, both federal and provincial governments have shown increased interest in promoting advanced ceramics by implementing new initiatives as well as supporting industry development programs. The most noteworthy initiatives are: (i) the establishment of Advanced Industrial Materials Directorate in the Department of Industry, Science and Technology; (ii) creation of a pre-competitive research support program by NRC to promote advanced ceramic industry; (iii) the creation of the Ontario Centre for Materials Research by the Province of Ontario; and (iv) the equity participation by the Alberta government in Edo Corporation of Calgary to develop an advanced ceramics and composite industry.

7.2 Manufacturers of Advanced Ceramic Powders

The manufacturers of advanced ceramic powders in Canada are listed in Table 55.

Alcan Aluminum Limited

Alcan Aluminum Limited., of Montreal participates in the ceramic powder business through its subsidiaries. Alcan Chemicals Limited., and Alcan International Limited.

TABLE 55

Manufacturers of Advanced Ceramic Powders in Canada

COMPANY NAME	PRODUCTS
Alcan Aluminum Limited- Alcan Chemicals Ltd. (Montreal, Quebec)	Alumina and zirconia powders
Alcan International, Ltd. (Kingston, Ontario	Non-oxide powders R&D on SiC, AlN, etc
Cancarb Limited (Vancouver, B.C)	Beta Silicon carbide
Electrofuel Manufacturing Co (Toronto, Ontari)	Boron nitride Aluminum nitride
Montreal Caride Co. Limited (St.Bruno, Quebec)	Titanium diboride- metal
Northern Pigment Company (Toronto, Ontario)	Iron oxides for ferrites
Macro Division - Kennametal Inc (Port Coquitlam, B.C.)	Primary carbides (WC, TaC, NbC, TiC etc) Mixed carbides

Alcan Chemicals Limited., is an integrated global enterprise and the management is organized to ensure that Alcan's various chemical operations share technology, product knowledge and product development efforts. It produces a diverse range of chemical products which include: normal and low soda alumina of varied crystal shape and size; reactive aluminas for advanced ceramic applications; and magnesium alloys and chemicals for advanced ceramics. These products are produced in Canada, U.K., and Japan. The Canadian operations are located in Arvida, Quebec and in Ottawa and Brockville, · Ontario. In the U.K., BA Chemicals manufactures alumina based chemicals for the U.K., and European markets. Alcan's 50% ownership of Nippon Light Metal Company Ltd., in Japan provides access to products and processes in the specialty aluminas and hydrate field. NLM's Shimuzu Works produces a wide range of high quality aluminum hydroxides and aluminas for the world market. Magnesium Elektron manufactures zirconia powders both in the U.K., and in the U.S.

Alcan International Limited., is the research arm of Alcan Aluminum Limited with laboratories both in Canada and in the U.K. The Kingston Laboratory is involved in the development of both advanced ceramic powders (both aluminas and non-oxide powders such as silicon nitride and aluminum nitride), and advanced structural ceramics (lanxide process).

Cancarb Limited

Cancarb Limited., is a wholly owned subsidiary of TransCanada Pipelines. It is the world's largest manufacturer of high quality carbon black sold under the trade name "Thermax". The manufacturing plant is located in Medicine Hat, Alberta, and produces about 70 million pounds of carbon black products per year. The Head Office of the company is located in Vancouver, B.C.

Advanced Refractories Limited., of Buffalo, a manufacturer of advanced ceramic powders, uses Thermax carbon blacks in the manufacture of silicon carbide and other carbide-based ceramic powders.

Cancarb has acquired process technology for the synthesis of high quality beta silicon carbide powders. It is understood that they are developing manufacturing technology. To this end they have received financial asistance from the Province of Ontario and are being assisted by the Ontario Research Foundation. According to published information, the powders are expected to be most suitable for the manufacture of advanced structural ceramics, electronic components and metal-ceramic and ceramic-ceramic composites.

Cancarb possesses a well established international network of agents and plans to market its beta silicon carbide powders in the international market.

Electrofuel Manufacturing Company Ltd

Electrofuel Manufacturing Company Ltd., is located in Toronto, Ontario. It is a relatively new company and is involved with both advanced ceramic powders and advanced structural ceramics.

The company has developed technology for the manufacture of both boron nitride and aluminum nitride powders. Boron nitride powders are sold as required, however, aluminum nitride powder is still under development.

Montreal Carbide Co Limited

Montreal Carbide Co Ltd., specializes in the development of advanced ceramic powders for use in plasma spray coatings on metal parts and components, particularly to increase their wear resistance. In addition, monolithic wear resistant parts and powder injection devices are also manufactured.

The company is located in St.Bruno, Quebec. It is involved in the commercialization of titanium diboride-metal powders developed by IMRI-NRC for wear resistant plasma coatings. The company plans to develop a series of powders which will provide flexibility to vary both the concentration of titanium diboride and the composition of metal to achieve optimum performance for specific applications.

The products are expected to be sold throughout North America and Europe.

Northern Pigment Company

Northern Pigment Company, a Division of Federal Industries, Industries Group Inc.,(formerly a Division of Canadian Corporate Management Limited) is located in Toronto. The company manufactures both natural and synthetic iron oxides comprising 50 distinctive colour shades from yellow to red, brown, green and black. Specific powders are used in the manufacture of ferrites, both hard ferrites and soft ferrites. It is one of the principal suppliers of specialized iron oxides used in the manufacture of ferrites.

Macro Division-Kennametal Inc

Macro Division of Kennametal Inc., is a wholly owned subsidiary of Kennametal Inc., of U.S. It was established in 1952 by Mr.Philip McKenna in its present location in Port Coquitlam, B.C. At present, the company employs about 60 people including production workers and R&D staff. The company has a strong R&D base which is used to develop new materials as well as to assist end users in the development of improved products.

Macro Division produces and markets four broad varieties of products. They are

- Intermediate carbides and nitrides such as: WC, TiC, WC/TiC, TaC, TiN, and TaC/NbC;

- fully prepared hard-metal carbide powder blends such as: those made by comminuting and blending the various carbides and auxiliary minor alloys such as cobalt;

- diamond tool matrix powders such as: W, WC, to make diamond-set and impregnated tools; and,

- hard facing products such as: gas and electric hardfacing welding rod composite rod and pads, flame and plasma spray powders as well as bulk tungsten carbide powders.

The company has a mandate to add the production of silicon nitride powders to its product line. It is understood that it is negotiating technology transfer from a number of international companies, including Toshiba Ceramics of Japan.

The company markets its products in 35 countries throughout the world, both to Kennametal divisions, subsidiaries and outside customers. The company has established its market base in Japan for over 15 years, and is an important supplier of metal carbide and nitride powders.

7.3 Manufacturers of Electroceramics in Canada

The manufacturers of advanced electroceramic products in Canada are listed in Table 56. Manufacturers of semiconductors and electronic products have not been included in this study because they are basically users of electroceramics.

Almax Industries Ltd.

Almax Industries Limited., located in Lindsay, Ontario, specializes in the manufacture of PZT ceramics, high frequency ceramics, and superconducting ceramics and powders. Through joint agreements, it also offers specialized ceramics for sensors that can operate from sub-zero to 1000 C. In 1987, the company employed about 100 people.

The company has a strong R&D department and has established technology transfer agreements with several companies in France, India, England, Denmark, Israel and Japan. It was the recipient of the

TABLE 56

Manufacturers of Advanced Electroceramics in Canada

COMPANY	PRODUCTS
Almax Industries Ltd. (Lindsay, Ontario)	PZT ceramics; High Frequency Ceramics; Sensors; Super-conducting ceramics
B.M. Hi-Tech Inc. (Collingwood,Ontario)	PZT ceramics; sensors; IR glasses Process Instrumentation; NDE Components to 50 MHz
Crystar Research Inc. (Victoria, B.C.)	Ultra pure and doped sapphire; Opto-electronic materials
Lakeside Electronics Ltd. (Whitby, Ontatio)	PZT ceramics; Conductive inks and pastes.
Murata Erie North America Ltd. (Trenton, Ontario)	Ceramic capacitors; Low pass filters; other electronic components.
Neosid (Canada) Ltd. (Toronto, Ontario)	Ferrite cores; magnetic components.
Powerplex Technologies Inc. (Downsview, Ontario)	Beta-alumina ceramics for Na-S batteries.

Canadian government "Award for Excellence in Technology Transfer in 1986 for developing new products based on technology transferred from government laboratories.

B.M.Hi-Tech Inc.

B.M. Hi-Tech Inc., located in Collingwood, Ontario, produces a full range of advanced piezoelectric materials and acoustic components including sensors. These products have been developed through close cooperation with its customers, and represent the desired range of materials as are known to day. The company products include:

- Piezoelectric ceramics: modified compositions of lead zirconate titanate, lead metaniobate and lead titanate;
- IR glasses, glassceramics and laser materials;
- sensors and devices: monolithic, multilayer and composite;
- non-destructive evaluation (NDE) components; and,
- process instrumentation: custom designed systems.

The company also provides services in: custom fabrication of ceramics; pressure sintering; silver, gold and nickel metallization. and MIL-STD compliance and certification. The company presently exports its products to the U.S., and to EEC countries for both OEM and other applications.

Presently, the company has a total staff of 10.

Crystar Research Inc.

Crystar Research Inc., of Victoria, B.C. is a subsidiary of Cominco Ltd. It is a new company established in 1987 and brings together 25 years of electronic materials experience into the field of advanced optical materials. Presently, it has a technical staff complement of 5.

Present facilities include a Czochralski crystal puller and advanced polishing and characterization equipment. Sapphire crystals up to 5" in diameter and 14 kg. in weight can be grown.

The current products are:

- Ultrapure and doped sapphire (including ruby) crystals in all popular orientations up to 5" diameter;
- precision custom fabricated shapes such as: wafers, lenses,

bars, and rods.

The company is also developing rubies and garnets such as YAG, YIG and GGG. Potassium titanyl phosphate (KTP), beta-barium borate (BBO) and lithium niobate are being developed for future production. Flux growth techniques for manufacturing crystals are also being developed.

Sapphire crystal products are used to make lenses for infrared applications; polished wafers are used as hosts for microelectronic circuits and infrared detectors. YAG and ruby crystals are used for solid-state laser applications. KTP, BBO and lithium niobate crystals will be used for light signal processing technology. These "non-linear" crystals can change the wave length of existing lasers to provide new applications.

Crystar Research Inc., has R&D contracts with European aerospace companies. The products are custom made and are destined for international markets.

Lakeside Electronics Ltd.

Lakeside Electronics Ltd., located in Whitby, Ontario, is a wholly Canadian company. It was founded in 1969 to produce custom-made electroceramics. The manufacturing and laboratory facilities occupy about 8,000 square feet of space. The number of staff is 6.

The company's main products are:

- PZT ceramics made to customer specifications for use in depth sounding sonar, fish finders, and other ultrasound devices; and,

- conductive inks and pastes for a variety of ceramic, glass, and plastic substrate applications in the manufacture of electronic components.

A significant part of the company's activities involve research and development in the field of ceramics and conductive coatings.

The company markets its products both in Canada and in the U.S.

Murata Erie N.A. Ltd.

Murata Erie N.A. Ltd., is a Canadian company and is part of Murata Erie N.A. Inc., which has its Head Offices in the U.S. It draws on more than 50 years of experience in the electronic component industry and has been manufacturing ceramic based EMI filters at its Trenton, Ontario, facility for more than 25 years. High voltage

multipliers and power supplies, which are manufactured in its Toronto facility, have been its product mandate for more than 17 years.

The company has a well established in-house design and manufacturing facility along with MIL approved QA/QC test facilities as well as modern production equipment. The total employment in the Canadian operations is about 1000.

The company manufactures ceramic capacitors in several specialized configurations including tubular capacitors, discoidal capacitors, (multi-hole) planar capacitors and high-voltage capacitor banks.

The applications for the company's products include medical, communications, commercial, military and aerospace products. The products are sold throughout North America through Murata Erie N.A. Ltd., and is represented world wide by Murata Manufacturing Co., of Japan, its parent company.

Neosid (Canada) Limited

Neosid (Canada) Limited., is one of the members of the Magnetic Materials Group Plc., companies of the U.K. It has been manufacturing ferrite cores since 1952. At first it produced only Powdered Iron Cores and in the 1960's added the production of ferrite cores. This mix of products is still in active production, and has recently been expanded to take advantage of new materials develped by its parent company, MMG.

The original facilities have been recently expanded to house an expanded office and laboratory facilities. The present employee strength is between 20 and 30.

The products of the company are:

- Different types of cores: powdered iron E-cores, hollow cores, insert cores, rods etc;
- choke forms;
- ferrite beads and toroidal cores; and,
- magnetic components for the electronics industry.

Canadian production is primarily for the domestic and U.S. markets. Nevertheless, the products are exported to South American countries, Australia and Europe.

Powerplex Technologies Inc

Powerplex Technologies Inc., is a joint venture between Magna International Inc., of Toronto, Ontario and ASEA, Brown, Boveri of W.Germany, formerly Brown, Boveri & Cie. The company was incorporated in 1984 and employs about 35 people in its 20,000 sq.ft. R&D facility in Toronto.

The controlling partner, Magna International Inc., is the largest Canadian automotive parts manufacturer with annual sales exceeding $1 billion. Magna designs, develops and manufactures a broad range of automotive components and systems for sale primarily to the North American original equipment manufacturers. ASEA, Brown, Boveri., is primarily involved in the design, development and manufacture of electrical products ranging from turn-key power generation plants to microelectronics.

Powerplex has an exclusive agreement with ASEA, Brown, Boveri., to jointly develop Na-S batteries and electric drive-trains for the North American market. It is involved in all aspects of Na-S battery development including microelectronics, electrochemistry and beta-alumina ceramics development. In the area of advanced ceramics, current activities are focused on improving the performance of ceramic electrolyte under the high temperature, highly corrosive conditions encountered in the electrochemical Na-S battery cell. Volume production of beta-alumina electrolyte tubes are planned for the future.

The following products are under development for use in the Na-S battery.

- Beta-alumina ceramic electrolytes, sulfur/graphite composite components;
- thermal insulation systems;
- high temperature microelectronic components; and,
- thermal management systems.

7.4 Manufacturers of Advanced Structural Ceramics in Canada

The manufacturers of advanced structural ceramics in Canada are listed in Table 57. Existing technical ceramic products manufacturers are diversifying into advanced ceramic products. Many new companies have started to manufacture different types of ceramic products.

TABLE 57

Manufacturers of Advanced Structural Ceramics in Canada

COMPANY	PRODUCTS
Alcan Aluminum Ltd. (Montreal, Quebec)	Lanxide products (Presently manufactured in U.S.)
Ceramics Kingston Inc. (Kingston, Ontario)	Carbide, Borides, Nitrides, Composites,
Datco Technology Ltd. (Burlington, Ontario)	Fire safety ceramics
Edo Canada Ltd. (Calgary, Alberta)	Ceramics for defence and aerospace applications
Electrofuel Mfg. Co.Ltd. (Toronto, Ontario)	BN monolithics & felts AlN, Composites (TiB_2 Si_3N_4 Al_2O_3- SiC, etc. Wear parts.
E Y C Technical Ceramics Ltd. (Espanola, Ontario)	High density Al_2O_3, PSZ, SiC, Si_3N_4.
Hamilton Porcelains Ltd. (Brantford, Ontario)	Cordierite, Zircon, Silicates, Mullite.
Hard Materials Research Inc. (Mississauga, Ontario)	Abrasion and wear products
Industrial Ceramics Limited. (Mississauga, Ontario)	Alumina refractory shapes Zirconia, Zircon & MgO products

TABLE 57 (Cont'd)

Manufacturers of Advanced Structural Ceramics in Canada

COMPANY	PRODUCTS
Inco Limited (Toronto, Ontario)	Ceramic coated metal parts
Kennametal Ltd. (Toronto, Ontario)	Cutting tools, Si_3N_4, Al_2O_3, Al_2O_3/TiC, Cubic BN,
MPB Technologies Inc.(*) (Dorval, Quebec)	Ceramic-metal seal technology High technology R&D
Norton Advanced Ceramics Canada Inc.Niagara Falls,Ont.	Products made by Norton Co. Al_2O_3, SiC, Si_3N_4, products.
Polyceram Inc. (Montreal, Quebec)	MgO, CaF products Beta-alumina products
Quality Hermetics Company (#) (Toronto, Ontario)	Hermetic seals (glass-metal glassceramic-metal)

(*) & (#) These companies do not manufacture advanced structural ceramics, however, provide services related to the use of advanced ceramics.

Alcan Aluminum Limited

Alcan Aluminum Limited., of Montreal has, as a corporate policy, decided to diversify into non-aluminum businesses which are expected to form at least 25% of its sales in the 1990's. As one of the diversification moves, the company entered into a joint development and commercialization agreement with Lanxide Corporation of the U.S., to jointly develop and commercialize lanxide products.

According to the available information, Alcan Aluminum Limited will not go into advanced ceramics manufacturing business by itself, however, will expand the product lines of the powders it sells to this industry. It plans to participate in the development and commercialization of lanxide products. As a first step, it has participated in a joint venture with Lanxide Corporation. A new company, Alanx, has been set up in the U.S.

It is understood that when the development and marketing in the U.S. is successfully implemented, Alcan may start a Canadian operation in Arvida (or close by) to take advantage of the aluminum smelting facilities and cheap electric power.

Ceramics Kingston Inc

Ceramics Kingston Inc., is a new company and started its activities in 1987, It is located in Kingston, Ontario. The company plans to conduct its business through 5 divisions: Structural Ceramics Division; Electronic Ceramics Division; Bio-ceramics Division; Space Technology Division; and, Marketing & Technology Brokerage Division.

The company plans to develop and market products which include carbides, borides, nitrides and composites.

Datco Technology Ltd

Datco Technology Limited., is a wholly Canadian owned company located in Burlington, Ontario. The company is affiliated with J.O.Bernt and Associates Ltd., a Canadian firm specializing in the design, manufacture and installation of high temperature industrial heat exchange systems. It shares the latter's manufacturing facility comprising about 10,000 square feet of space. The present staff consists of two engineers with the required number of production staff.

Datco is developing advanced fire safety materials/systems using advanced ceramic technology. Presently, the company is developing fire resistant coatings for the Canadian Department of Defence for use in naval vessels. Modified versions of these

coatings are being evaluated for commercial markets in Canada and in the U.S.

The company plans to expand its activities to include other advanced ceramics including alumina and zirconia based products.

Edo Canada Ltd

Edo Canada Ltd., is located in Calgary, Alberta. It started its operations in 1983, as a subsidiary of Edo Corporation of New York, NY, U.S.A., by acquiring a local manufacturer of electronic instrumentation. In December 1987, the ownership as well as the objectives underwent change. It is now jointly owned by the Government of Alberta and Edo Corporation. The operations have been expanded to include the development and and manufacture of advanced structural ceramics and composites.

In order to implement the expanded objectives, Edo Canada Ltd., will operate three Divisions:

- Electronics
- Advanced Composites
- Advanced Structural Ceramics

The Elelctronics Division will continue its present mandate.

The Advanced Composite Division is now being organized and is expected to go into operation by the middle of 1988. Both the technology and product lines are being supplied by the Edo Corporation from its U.S. operations as part of the joint venture agreement with the Alberta government.

The advanced Structural Ceramics Division will obtain its ceramics processing technology from Edo Corporation's U.S. activity. However, the appropriate product lines are still being finalized. The company plans to acquire the required technology for the selected product lines through licencing agreement as well as in-house R&D. The company plans to establish an R&D laboratory for the development of technology and new products.

Edo Canada Ltd., has been active in international markets since its inception, selling satellite positioning instruments. Historically, 70% of the sales have been in the international markets. The company hopes to sell advanced composite and advanced structural ceramic products globally using the experience and expertise of one of the joint venture participants, the Edo Corporation.

Electrofuel Manufacturing Co. Ltd

The Electrofuel Manufacturing Co.Ltd., was founded in 1983 to specialize in the development and manufacture of LiAl-FeS batteries. However, the experience gained by the company in the development of boron nitride battery separators using advanced ceramic technologies, as well as the opportunities and market potential for advanced ceramics acted as catalysts in expanding the scope of the company to become a manufacturer and supplier of advanced ceramic materials and high technology specialized products.

The company is technology oriented and has over 10,000 square feet of R&D space and about 20 R&D personnel. The company also has extensive manufacturing facilities. In addition to standard advanced ceramic processing equipment and facilities, Electrofuel has a custom-designed high-temperature (2200 °C), high-pressure (50,000 psi) hot press with capabilities to form components with diameters up to 12 inches.

Electrofuel manufactures a diverse range of products which include:

- Monolithic boron nitride (BN) ceramics used as break rings in continuous casting of steel, kiln furniture, insulators, heat sinks, and crucibles for melting glasses and metals;
- boron nitride fibres for battery separators, high temperature gaskets & rotary seals, high temperature insulation, and for composites;
- AlN powders and ceramics;
- Alumina - SiC whisker composites for cutting tool, extrusion dies, valve and pump components;
- titanium diboride based evaporating boats;
- toughened alumina for cutting tools and parts for wear resistant applications;
- wear resistant parts made of SiC, Si_3N_4, TiB_2 etc; and,
- specialty furnaces: hot press, sinter HIP and dilatometer for HIP.

The company maintains marketing and technical contacts in Canada, U.S., Japan and in Europe. Its products are sold both directly and through its distributors.

EYC Technical Ceramics Ltd

EYC Industries Limited., is a wholly owned subsidiary of Almax Industries Limited. It was established in 1984 in Espanola, Ontario, to provide wear and heat resistant ceramic tiles for the resource industries of Northern Ontario. Almax Industries acquired the company in 1986, and set up a second facility in Lindsay, Ontario devoted to engineering and market development as well as for the manufacture of new product lines. In 1987, the staff numbered 9.

The following product lines were being manufactured in 1987:

- Slip Cast Ware: This is the main product line at the Espanola facility. High purity alumina crucibles and kiln furniture are manufactured to customer specifications.

- Wear Tiles: This product is handled as a resale item, however, some specialty tubes are manufactured in-house.

- Machined Ceramics: carbide and diamond machining capabilities are set up in the Lindsay facility to produce precision components of alumina and zirconia ceramics.

- Filter Plates: EYC has developed ceramic membranes for specialized applications such as: components used in persulfuric acid production, electrolytic sensors, high temperature electrolysis, and extreme temperature gas filtering.

- Armour Plates: EYC has developed a process for the manufacture of toughened alumina products by a proprietary casting and sintering procedure that produces a tough thick outer layer. The material can be machined to the required configuration in the prefired state, if required.

- High temperature kiln: EYC, under licence from a French company, manufactures a high temperature laboratory kiln that will operate in an oxidizing or neutral atmosphere at 2200 C. The kiln is available in several sizes.

Hamilton Porcelains Limited

Hamilton Porcelains Limited., is a privately owned Canadian company which began operations in 1852. It originally produced artware and household ceramic products in Hamilton, Ontario. The company moved to Brantford, Ontario, in 1946 and diversified its product lines to include industrial products. Over the years, the company discontinued the artware and household ceramic product lines and became a technology oriented company.

At present the company operates three manufacturing facilities. The plant in Brantford continues to produce existing product lines to meet the requirements of longstanding customers. Very recently (1987) a new facility has been commissioned in Paris, Ontario, which incorporates "state-of-the-art", fully-automated, microprocessor-controlled equipment for the manufacture of specialty products developed in-house in the company's R&D laboratory.

The third facility, Brantford Heaters Limited., manufactures a complete line of gas-fired as well as electric infra-red radiant heaters.

The company employs a total of about 140 people.

The product lines include:

- Triaxial electrical porcelain (low-medium voltage);
- zircon materials for high strength refractory shapes e.g., high voltage arc chutes and switch gear components;
- cordierite perforated honecomb ceramic tiles for infra-red radiant heaters;
- semi-cordierites for highly specialized shock resistant applications; and.
- mullite-pyrophyllite hybrid refractory shapes for filtration of metals used in the manufacture of automotive components.

The company has established an international market for its products. 75% of its production is exported to the U.S., South America, Mexico, Puerto Rico, Japan, Italy, W.Germany, Belgium, Spain, Sweden, Korea, Ireland and India.

Hard Materials Research Inc

Hard Materials Research Inc., is a Canadian company which started its operations in 1986. It is jointly owned by Boart Canada Inc., a manufacturer of mine drilling equipment and related products, and Chadrien Ltd., an engineering consulting company.

The objectives of the company are: to provide contract R&D services to industry and governments; and to develop new technology and/or materials for commercial exploitation.

The Mississauga, Ontario, facility of HMR houses pilot scale equipment for blending, milling, drying and granulation of hardmetal

powders, as well as the pressing and sintering of cemented carbide components. The total staff complement at present is four, however, is expected to grow as demand for services increases.

Presently, the company provides services in the following areas:

- Evaluation of wear problems;
- development of specialized hard materials;
- production and testing of cemented carbide products; and,
- technical and economic surveys and feasibility studies.

Inco Limited

Inco Limited., is the world's leading producer of nickel, copper, precious metals and cobalt. It is also the world's largest supplier of wrought and mechanically-alloyed nickel alloys as well as a leading manufacturer of blades, discs, rings and other forged and precision-machined components made from special alloy materials used in gas turbine engines.

Inco is a Canadian company and carries on its operations and activities in 19 countries. The total employment in 1987 was about 20,170. The net sales value for 1986 was about US$ 1.45 billion.

J.Roy Gordon Research Laboratory is located in Sheridan Park, Ontario, and is the extractive metallurgy research laboratory of Inco. While the laboratory mainly does extractive research for its operating divisions, it also does research with the alloy division on the development and use of advanced ceramic coatings.

The advanced ceramic coating development work involves coating Inco special alloys with ceramics using Physical Vapour Deposition (PVD) and plasma coating techniques. The total man-year effort in this area is about 5-10/year.

The products are still in the development stage. Primarily, these will be alloy components manufactured by Inco Alloy and Engineered Products Division with protective ceramic coatings for high temperature and special environment applications.

Industrial Ceramics Limited

Industrial Ceramics was established in 1946 and is wholly Canadian owned. It also has a U.S. subsidiary.

The company has enlarged its R&D activities recently to take advantage of new opportunities for advanced ceramic products. In addition to in-house R&D effort, the services of other establishments such as the Ontario Research Foundation are used, as required.

The manufacturing plant and the R&D laboratories are located in Mississauga, Ontario. The company employs 3 technical staff and about 20 production workers.

The present product lines include: special refractory shapes in alumina, zirconia, zircon and magnesia.

The company has been marketing its products throughout the world for over 25 years.

Kennametal Limited

Kennametal Ltd., is a wholly owned subsidiary of the U.S. owned Kennametal Inc., the world's largest producer of hard carbide alloys. The U.S. Corporate Head Office is in Latrobe, PA. The Canadian Head Office is located in Toronto, Ontario, with manufacturing facilities in both Toronto and in Langford, B.C. The company employs a total of about 230 people including about 5 in R&D and engineering and about 110 production workers (about 30 in Toronto and about 80 in Langford). The sales offices and/or distributors are located all across Canada.

Kennametal Ltd., markets all the products and services available through its parent company which has long been recognized as a quality leader in the manufacture of metal cutting, metal-forming products, and other abrasion, wear and corrosion resistant products.

The different types of cutting tool materials manufactured by Kennametal Inc., are:

- Silicon nitride (sialon) ceramics
- Alumina-based "whisker" reinforced ceramics
- Alumina/TiC ceramics
- Alumina ceramics
- Cermet (TiC/TiN)
- Polycrystalline diamond
- Cubic boron nitride (CBN)

In Canada, Kennametal Ltd., manufactures tungsten carbide and diamond based products, both coated and uncoated. They include: cutting tool inserts, stationary and rotating tool holders, workh-olding devices, collets and chucks, drills, boring bars, mill cutters and numerous accessories.

Kennametal supplies other products for demanding wear and specialty applications. These products are engineered to take advantage of one or more of the characteristics of tungsten carbide or other materials such as: high hardness and density, compressive strength, exceptional resistance to wear, corrosion and pressure.

Bulk of the hard carbide powders used in the manufacture of the products are supplied by its sister company, Macro Division of Kennametal Inc., Port Coquitlam, B.C.

MPB Technologies Inc

MPB Technologies., was incorporated in 1976 under the federal charter. It specializes in the development of high technology products as well as R&D in fields ranging from electromagnetics, to telecommunications, lasers, fusion, electro-optics and space technology.

In the area of advanced ceramics, the company has specialized in the development of reliable high-temperature, vacuum-tight, hard seals technologies for the bonding of several combinations of materials such as: ceramic-to-ceramic and ceramic-to-metal (kovar, stainless steel, platinum etc) seals. the company provides R&D as well as custom manufacturing facilities in hard seals as well as other high technology products.

Norton Advanced Ceramics Canada Inc

Norton Advanced Ceramics Canada Inc., is wholly owned by Norton Company of the U.S., with Head Offices in Worcester, MA. Norton Company also operates a Research & Development Centre in Chippawa, Ontario, to support its worldwide activities. The Centre has a staff of about 30-40.

Norton Company worldwide operations are grouped into: Abrasives; Engineering Materials; and, Petroleum and Mining. The products are:

- ABRASIVES: Bonded grinding wheels, coated abrasives, construction products, and diamond wheels & tools.

- ENGINEERING MATERIALS: Chemical process products, health care products, high performance ceramics, industrial

ceramics, high performance plastics.

- PETROLEUM AND MINING: Drilling products, drilling systems, mining products & services, proppants, and well services.

Norton Advanced Ceramics Canada, Inc., specializes in meeting the advanced ceramic requirements of Canadian industry by providing:

. Technical assistance in the selection and use of advanced ceramic components/products for specific industrial uses;

. market research and business development expertise - from development to commercialization; and,

. advanced ceramic components and products manufactured by Norton Company.

Polyceram Inc

Polyceram Inc., was founded in 1975 by a group of scientists associated with Ecole Polytechnique, Montreal. The company has a total staff complement of 3.

The following products are made by Polyceram:

- Magnesia Products: These are excellent for use to contain corrosive melts such as basic slags, oxides, salts, or metals.

- Calcium Fluoride Products: These are ideal for containing molten metals when thermodynamic stability and minimum contamination are essential. They can also be used for solid electrolyte applications.

- Beta-alumina: Application for these products include probes, electro-chemical sensors for on-line chemical analysis, thermodynamic measurements etc.

Quality Hermetics Co

Quality Hermetics was founded in 1955 and later acquired by Leigh Instruments Limited., in 1969. It holds an unique position in Canada as the only manufacturer of glass-metal and glassceramic-metal hermetic seals.

The company is technology intensive and has carried out R&D programs for more than a decade aimed at developing hermetic seals for severe environments, e.g., nuclear reactors, deep well oil & gas drilling, aerospace gyros etc. It has the expertise to address ceramic-metal joining techniques for industrial applications.

7.5 Industrial Plasma Coating Facilities in Canada

Canada has a number of well equipped industrial plasma coating facilities. Some of them have more than two decades of experience. The capability of these companies is considered to be excellent. Three of them provide services to the aerospace industry. The list of industrial plasma coating companies in Canada is listed in Table 58.

JaCoat Company

JaCoat Company is a division of George A. Wright & Son which was established in 1896 to provide metal machining services to industry. Presently, the company employs about 40 people.

JaCoat was established in 1976 to provide wear resistant coatings to improve textile machinery components used in the manufacture of synthetic fibres. Subsequently, many other industrial uses have been developed. Coating services are provided to the pulp & paper, cable & pump manufacturing and gas turbine industries. The coating facility employs 8 workers.

In addition to plasma and flame coatings, JaCoat provides full machining and metal fabrication services to its customers. Both high and low velocity systems are used in providing the required coatings. The equipment capabilities include two Metco plasma units (one 40 kW and one 80 kW) and metal machining and preparation facilities.

The coatings include oxides, carbides and metals and are custom designed to provide wear and abrasion resistance to parts and components used by industry. the company has developed specialized technology to control the quality and thickness of the plasma/flame coatings to meet severe operating conditions.

JaCoat has provided development services to companies in the U.S., Japan, South Africa as well as to member companies of the British Surface Engineering Society.

Jay-Em Ceramics

Jay-Em Ceramics is a Division of Jay-Em Inc., a private Canadian holding company. It was founded in 1986 to provide custom-designed advanced ceramic coatings to meet the needs of Canadian industry, particularly for wear, abrasion and corrosion resistant applications.

Whereas the company provides standard state-of-the-art coatings for routine applications, its unique strength is its scientific and technical capability in providing custom-designed plasma coatings to meet client needs and requirements. In many instances, the company acts as the R&D arm of its client to develop and apply optimum plasma

TABLE 58

Industrial Plasma Coating Facilities in Canada

COMPANY	ADDRESS
JaCoat Company	Mr.D.C. Radford, Manager 146 Hickson Avenue Kingston, Ontario, K7L 4VR (613) 548-3128
Jay-Em Ceramics	Mr.S. Johar, General Manager 8 Melanie Drive Brampton, Ontario, L6T 4L2 (416) 458-8638
Metal 7 Inc	Mr.C. Bigonesse, General Manager 285 des Pionniers Sept-Isles, Quebec, G4R 4X9 *418) 968-5822
Peacock Inc	Mr.M. Sikich, General Manager 1180 Aerowood Drive Mississauga, Ontario, L4W 1Y5 (416) 625-7100
Plasma & Flame Coatings	Mr.J.W.H. Blott, President 1975 Logan Avenue Winnipeg, Manitoba, R1R OH8 (294) 632-5585
Standard Aero Ltd	Mr.B.R. Junkin, Manager Engineering Technical Service 33 Allen Dyne Road Winnipeg, Manitoba, R3H 1A1 (204) 775-9711
Vac-Aero International Inc.	Mr.L. Gosselin, General Manager 7450 Rue Verite St.Laurent, Quebec, H4S 1C5 (514) 334-4240

coatings to satisfy specific needs.

The facilities at Jay-Em Ceramics include a 80 kW Metco Plasma unit with supporting equipment. At present, the company is located in a facility with 1,000 square feet space, however, is considering a move to larger facility. The scope of the services provided include:

- Routine plasma coatings based on oxides, carbides, cermets, metal alloys and plastics.

- Advanced custom-designed coatings

At present, Jay Em Ceramics does not manufacture any products for commercial sale. However, it has an in-house R&D program to develop components based on superconducting advanced ceramic films.

Metal 7 Inc

Metal 7 Inc., is a Canadian company founded in 1975. Its Head Office and plant are located in Sept-Isles, Quebec. It was originally founded as a machine and metal-working shop to serve the needs of the resource industries of Quebec. Since the late 1970's, it has evolved into a manufacturer of high technology, high performance industrial parts and components using thermal spray and plasma coating technology.

The company's expertise lies in using plasma spray coating technology to apply thin but highly durable ceramic, metallic and cermet coatings on components and parts subject to heavy wear. The sales of ceramic coated components has increased from 5% of total sales in 1981 to about 75% in 1987, and is expected to grow further.

The company employs a total of 35 people. The production staff is 26 and the engineering staff is 5; the latter is expected to grow to 10 in 1988.

Almost 80% of the sales of coated products are concentrated in the iron ore industry. Screen deck roll, in particular, is the only product for which the company has developed a volume application. All other applications are essentially low volume specialized parts and components. This is true even for the pulp and paper industry which represents the company's second largest market.

Recent new product applications include:

. Casting grates, vibrating rods, liners for burners and valve bottoms for mineral separation - all for iron ore pellet plants;

. Mixing "fingers" and exterior structures for the pulp and

paper industry.

. Ball valves for the oil and chemical industries.

Metal 7 has extended its sales on the world markets in the early 1980's. In 1987 the company exported more than 50% of its production all around the world including U.S., Sweden, Netherlands, and India. The company plans to expand its sales to Liberia, Mexico and Turkey.

Peacock Inc

Peacock Inc., is a Candian company founded in 1897. The company operates two divisions:

- Industrial Products Division

- Industrial Services Division

The Industrial Products Division manufactures and distributes filtration products, material handling equipment, pumps and instruments of all types.

The Industrial Services Division operates six fully equipped Service Centers located in Montreal, Toronto, Calgary, Edmonton, Fort St.John and Fort McMurray. These Centers provide around-the-clock specialized repair and rebuild service for a wide range of small, medium and large scale industrial equipment.

The following types of services in advanced ceramic coatings are provided:

. Plasma transferred arc welding
. Flame spray systems
. Hard surfacing
. Specialty grinding and super finishing
. Machinery repairs and rebuilds
. Industrial repairs and rebuilds
. Custom parts
. Machinery field service
. Flame spraying and centrifugal casting

The following products are sold by the company:

. Pumps and valves
. Filtration systems
. Material handling systems
. Filter replacement cartridge
. Measuring devices of all kinds

Plasma & Flame Coatings Limited

Plasma & Flame Spray Ltd.,is a wholly Canadian owned company. It was started in 1971 in Winnipeg by Mr.Blott, the President of the company who had acquired extensive experience in plasma coatings as an engineer with Metco operations in Canada for over 16 years.

The company occupies about 18,000 square feet of space with a staff complement of 25. Five Metco plasma units, with capacity range to 80 kW, are in use with one spare. It specializes in plasma coatings for thermal, wear and corrosion resistant applications. It provides specialized coatings for the repair, maintenance and overhaul of: aircraft engine components and parts; pump parts for the oil and gas exploration industry; and components used in other industrial sectors such as pulp & paper, petrochemicals, mining and machinery. In addition, the company also manufactures original parts and components required by its customers.

In the aircraft engine area, the company does repair, maintenance and overhaul work for: Bristol Aerospace & Standard Aero in Winnipeg, and IMP Ltd., in Halifax, NS. All types of engines, e.g., Rolls Royce, Pratt & Whitney and General Electric, are serviced.

The pulp & paper industry is a very important sector for which the company provides specialized original plasma-sprayed components as well as repair and maintenance services. The components are sold throughout the world by its distributors.

In the oil & gas industry, plasma coating services are provided in a number of areas which include: pump components, diesel engine components and on-site coatings for corrosion protection for critical areas. Petrochemical indutry is also serviced.

Wear and abrasion protection coating services are also provided to the mining and machinery industries, e.g.,bearings, industrial fan components, etc.

Standard Aero Limited

Standard Aero Ltd., is a wholly owned Division of Avcorp Industries Inc., a diversified Canadian aerospace company. Through its operating Divisions, Avcorp is involved in production and servicing of an extensive range of metal, composite and specialized plastic components used in the aerospace industry.

Standard Aero provides a complete range of repair and overhaul services for a full range of gas turbine engines including:

- Allison 250 series
- Allison T56/501 series
- Allison 501-K industrial series
- General Electric T58 series
- Lycoming/Textron T53/T55 series
- Pratt & Whitney PT6A series

The company has in-house plasma spray and flame spray coating facilities which are used in the overhaul of gas turbine engines components.

Vac-Aero International Inc

Vac-Aero International Inc., was originally established in 1959 by engineers with many years of experience in the Canadian aircraft industry to provide braze and heat treatment facilities for metal components used by the aerospace industry.

The company operates two plants: the Ontario Division in Oakville, Ontario, and the Quebec Division in Montreal. The Head Office of the company is in Oakville.

The Ontario Division provides services in vacuum thermal processing which include: annealing and stress relieving; hardening and tempering; solution heat treating and aging; precipitation hardening; and sintering.

The Quebec Division provides all the plasma coating services. Manual, semi-automatic and computer-controlled robotic plasma coating techniques are used to achieve homogeneous coatings and uniform thickness. The Division employs about 15 people.

In the aerospace industry, coating services are provided for: gas turbine engine and air frame components; hot section thermal barrier coatings for combustion and after-burner liners; abradable seal coatings in high and low compressor casings. The customers include: Pratt & Whitney Canada, Rolls Royce and Air Canada.

Industrial coating services are provided to other industry sectors including: pulp & paper, chemical and pumps.

The coating materials include: ceramics, carbides, nickel, cobalt and molybdenum.

7.6 R&D Capabilities in Canadian Universities

Ceramic technology incorporates a wide range of academic disciplines - the most direct being ceramic engineering, but facets of it include industrial engineering, physics, chemistry, electronics, metallurgy and material science. The location of university expertise reflects this breadth - a situation which often makes activity in ceramics hard to identify and locate. Major groups in Canadian universities are listed in Table 59 and the specific expertise is summarized in Table 60 Only McMaster University has a formally acredited undergraduate engineering degree program in Ceramic Engineering; all the others carry out research and offer undergraduate and graduate courses in areas related to ceramics as part of the activities of other departments.

As can be identified from Table 59 Canada has a very good academic base in ceramics and related areas. Also, the universities are very active in both fundamental and applied research. The former is supported by NSERC and the latter by industry.

In recent years, the universities have played an important role in responding to the needs of Canadian industry. The formation of the Advanced Materials Technology Unit at Queens's University and the Canadian University-Industry Council on Advanced Ceramics are clear indications of the interest and initiatives shown by the Canadian academic community.

When compared to other countries, Canadian academic capabilities come next to the United States and Japan; They are considered to be as good as, if not better than the U.K., W.Germany and France. The future depends upon the support that can be harnessed to expand the existing base of expertise, particularly from industry and governments.

7.7 R&D Capabilities in Federal Government Laboratories

The principal Federal government (and Crown Corporation) laboratories active in advanced ceramics R&D are:

- CANMET - Department of Energy, Mines & Resources
- National Research Council of Canada
- Atomic Energy of Canada

7.7.1 CANMET - Department of Energy, Mines & Resources

Historically, the Ceramics Section of the Mineral Sciences Division, CANMET, is one of the oldest laboratories in Canada specializing in ceramics research. As is to be expected, the type and

TABLE 59

Canadian Universities Active in Advanced Ceramics R&D

UNIVERSITY	DEPARTMENT	RESEARCH DIRECTOR	STUDENTS	PROFESSIONAL/ TECHNICAL
Concordia	Chemistry	M.F. Bell	NA	5
Dalhousie	Dental-Bio Materials	D.W. Jones	2	2
Ecole Polytechnique	Metallurgy	M. Rigaud	9	12
Laval	Mining & Metallurgy	R. Angers	NA	2
McGill	Mining & Metallurgy	R.A..L. Drew	7	13
McMaster	Mat.Science & Engineering	P.S.Nicholson G.P.Johari	51	16
Queen's	Physics Metallurgy	M. Sayer V.D. Krstic	6 NA	5 NA
R.M.C.	Physics	B.K.Mukherjee	NA	7
Tech.U of Nova Scotia	Engineering Physics	H.W. King	5	2
University of British Columbia	Metals & Materials Engineering	A.C.D.Chaklader	NA	12
University of Sherbrooke	Faculty of Engineering	C. Roy	15 (*)	25(*)
University of Toronto	Metallurgy & Mat.Science	J.M. Toguri	NA	8
University of Waterloo	Physics & Chemistry	D.E. Brodie	NA	7
University of Windsor	Engineering Materials	H. Yamauchi	NA	2

(*) Includes all advanced materials activities

TABLE 60

University Research Areas in Ceramics

Research Area	Nova Scotia	Laval	Ecole Poly	McGill	Queen's	McMaster	UBC
Powder Processing			a	x		x	y
Sinter/hot pressing			b	x			y
Fabrication/processing			a, b	x		x	y
Thermodynamics/chemistry			a, b				
Mechanical Properties		x	a, b	x		x	
Fracture/failure analysis			a			x	
Erosion/degradation	x		a			x	
NDE/ultrasonics					x	x	
Electronic properties	x				x	x	
Ionic conductors, probes			b		x	x	
Refractories			a		x		y
Piezoelectrics					x	x	
Glasses/glass ceramics				x	x	x	
Zirconia/PSZ/oxides			a		x	x	
Aluminas			a, b	x	x	x	
Sialon/SiC/TiB_2		x		x			y
Composites/fibres					x	x	
Plasma spray	x				x		
Films/coatings	x				x		
Bioceramics				x		x	
Interfaces Ceramic/ceramic/metal	x	x		x	x		y
Instrumentation, Analysis, XRD	x			x	x		y

a — Rigaud b — Pelton y — Chaklader

scope of work has changed over the years to keep pace with changes in technology and the needs of Canadian industry. In the early days, most of the work was on Canadian clays to meet the needs of the existing traditional ceramics industry. During the second World War, the laboratories collaborated with NRC in developing the materials required for the atomic energy program. In order to support the developing electronics industry in Canada after the war, the laboratory pioneered in the development of piezoelectric ceramics based on barium titanate, an effort that resulted in a number of Canadian industrial companies in this area. Because of the energy crisis caused by the OPEC oil embargo in the early 1970's, the laboratory expanded its activities towards energy conservation and generation. One result of this move is the expertise developed in the field of ionic conductors for batteries and other applications. The Section has done pioneering work in this area and is recognized as one of the leading laboratories in this area in the world. Recognizing the need in Canadian industry for assistance in developing advanced ceramics, the laboratory has initiated programs in the development of advanced ceramic powders and advanced structural ceramics.

Presently, the Ceramics Section consists of 9 scientists and 4 technologists. The R&D programs are generic in nature, and are aimed towards the development of both traditional and advanced ceramic compositions, process technology and evaluation of properties. These activities can be grouped as follows:

- Electrical Ceramics: Piezoelectrics, ferroelectrics, dielectrics, and solid electrolytes;

- Composites: Toughened and re-inforced oxide and non-oxide ceramics;

- Refractory Materials: Evaluation of performance, microstructure and mechanical properties;

- Ceramic Powders: Synthesis of oxide and non-oxide powders using thermal, hydrothermal, sol-gel, metal-organic, spray-drying and freeze-drying techniques;

- Thermophysical Properties: Automated determination of thermal conductivity, thermal diffusivity and specific heat to 800 C.

One of the important features of the Section is its close involvement with industry and universities. In the past, the Section has been extensively involved with the technical aspects of a number of industrial programs funded by other federal agencies such as NRC and the Departments of National Defence, Regional Industrial Expansion, Communications, and Consumer and Corporate Affairs. This interaction is expected to continue in the future.

7.7.2 National Research Council

Over the years the National Research Council of Canada has been involved with ceramics development, e.g. during the second World War in the development of ceramics for atomic energy program. With the creation of the Industrial Materials Research Institute (IMRI) in the early 1980's, activities in ceramics increased. Now active R&D programs on both functional and structural ceramics exists.

The Research Divisions and Laboratories that are active in advanced ceramics R&D are:

- Chemistry (Ottawa)
- Mechanical Engineering (Ottawa & Vancouver)
- Microstructural Sciences (Ottawa)
- Canada Centre for Space Science (Ottawa)
- National Aeronautical Establishment (Ottawa)
- Industrial Materials Research Institute (IMRI) (Boucherville, Quebec)
- Atlantic Research Laboratory (Halifax, NS)

In functional ceramics, the activities are focused on: semiconducting ceramics, high -temperature superconductors, zirconia ionic conductors, optical coatings and piezoelectric-polymer composites.

In structural ceramics, the activities include: process technology, application in diesel and gas turbine engines, tribology, non-destructive evaluation, reactive plasma synthesis, ceramic fibre synthesis, ceramic-ceramic-metal joining.

Recently, NRC has implemented a coordinated in-house R&D effort on advanced structural ceramics. A group of 28 professionals are involved in various related activities. Some of the important R&D programs are:

- Monolithic and composite ceramics: process development for SiC, Si_3N_4, and ZrO_2 toughened alumina ceramics;
- Coatings: reactive plasma synthesis, plasma coatings based on TiB_2 in metal matrices;
- Non-destructive evaluation of monolithic ceramics and composites;
- Ceramic-ceramic and ceramic-metal joining;
- Development of SiC fibres and coatings from organic polymer precursors;

- Prototype testing and evaluation of ceramic diesel engine components;

- Hot isostatic pressing and mechanical properties related to gas turbine engine applications;

- Tribology.

In addition to operating its laboratories, NRC runs an extensive program of financial and technical support for industry. These services are delivered through the Industrial Research Assistance Program (IRAP). Recognizing the importance of advanced ceramics as an enabling technology impacting on a number of Canadian industrial sectors, NRC has instituted a new Program for Generic Pre-Competitive Cooperative R&D in Advanced Ceramics. Three areas that are presently being developed are: superconducting ceramics, non-destructive testing, and advanced structural ceramics for automotive applications.

7.7.3 Atomic Energy of Canada Limited

Atomic energy of Canada Limited., has been active in ceramics R&D for over 35 years. Years ago, AECL's Chalk River Laboratories developed technology for manufacturing uranium dioxide into ceramic fuel for the CANDU reactor. Today, in addition to ongoing work aimed at making CANDU fuel more versatile and efficient, it is applying its ceramics expertise to develop other types of technical ceramics.

A program jointly funded by AECL and the Canadian Fusion Fuels Technology Project is underway to develop fusion breeder blankets. A key part of this program aims to develop ceramic materials in the form of small spheres with optimized microstructures. Work is in progress to produce high-purity lithium aluminate via powder and colloidal routes, and to develop processes for producing lithium aluminate spheres.

An Advanced Ceramic Group was formed in April 1986 to identify and exploit commercial and business opportunities in ceramics. Instead of simply selling the skills via R&D contracts, AECL is encouraging joint-venture projects with industry i.e., AECL is investing in the development of products and processes with industrial companies to share in the business benefits.

AECL is combining forces with Hydro-Quebec and Canada Wire & Cable to initiate a joint consortium project on high temperature ceramic superconductors.

The Advanced Ceramic Group is also extending the technology developed for nuclear ceramics to a new program - the Thoria Products venture. Thoria is chemically inert under both reducing and

oxidizing environments and it has the highest melting point of all oxides (3300 °C). It is anticipated that thoria will replace uranium dioxide as the fuel for CANDU reactors. As a first step, the Ceramic Group has developed a line of thoria labware products consisting of crucible, tubes and combustion boats.

In addition to promoting joint ventures with industry, the Advanced Ceramics Group is offering the following services to industry:

- Consulting Services: technology audit; materials selection; process/product evaluation; NDT optimization.
- Contract R&D: Ceramic process/product development; NDT development;
- Specialized Products: thoria products; NDT instrumentation
- Technology licencing

7.8 R&D Capabilities in the Provincial Research Organizations

Four Provincial Research Organizations are active in the field of advanced ceramics. They are:

. Alberta Research Council
. Manitoba Research Council
. Nova Scotia Research Foundation Corporation
. Ontario Research Foundation

7.8.1 Alberta Research Council

The Alberta Research Council, started in 1921, is a Provincial Crown Corporation with a mandate to support and promote economic development in Alberta through scientific, engineering and technological research. It has a staff of 500 scientists, engineers and support personnel. ARC has been involved in materials research for some time, and has well equipped metallurgical, polymer and forest product testing facilities. However, programs in advanced ceramics are being expanded to provide assistance to industry via contract R & D and jointly-funded projects. The impetus for this is the recognition that advanced ceramics will play a very important role in many sectors of Albert's economy including oil & gas, petrochemical, agriculture, medical, electronics and telecommunications.

ARC is concentrating on plasma technology for improving wear, erosion and corrosion resistance properties of metal components and systems used in the oil & gas industry; this area was identified by the Alberta Industrial Materials Task Force of ARC.

7.8.2 Manitoba Research Council

The Manitoba Research Council established the Industrial Technology Centre (ITC) as a product development and testing facility to serve Manitoba industry. To this end, the Centre has become involved in a wide range of projects and is accredited by the Standards Council of Canada for specific tests registered with the Council.

In addition to providing assistance to Manitoba industry in the selection and use of advanced industrial materials, ITC provides specific assistance in the evaluation, selection and use of advanced ceramic coatings, specifically in the following areas:

- Plasma coatings for wear, abrasion and corrosion applications;
- Electrochemical techniques for depositing ceramic/metal coatings.

7.8.3 Nova Scotia Research Foundation Corporation

Nova Scotia Research Foundation was established in 1946 by the Province of Nova Scotia to use science and technology in assisting the economic development of the province.

Ceramic R&D at NSRFC was initiated in 1981 in cooperation with the Atlantic Research Laboratory of NRC. To date, work has concentrated on the development and evaluation of erosion resistant ceramics based on alumina. To facilitate these studies, a special fluidized-bed feeder for eroding ceramic targets with silicon carbide powders has been designed, constructed and evaluated.

Composition and process technologies for the fabrication of dense alumina parts have been successfully developed. Erosion resistant inserts for use in nozzles for burning coal-water slurries have been manufactured and sold.

Present activities include the development of advanced ceramic composites based on the alumina-zirconia system, particularly process related technologies including sol-gel techniques for the preparation of powders and pressure casting. Work related to processing of ceramics in microgravity is also in progress.

R&D in ceramics is a part of the materials technology activities the others being: mechanical and metallurgical testing; welding procedure qualification; failure analysis; and corrosion R&D.

7.8.4 Ontario Research Foundation

Ontario Research Foundation (ORF), is a comprehensive technology consulting enterprise serving commercial and governmental organizations. It helps business to innovate through product and process development, and to improve productivity, product and competitiveness. ORF serves more than 2,000 clients annually. Work is done on a fee basis, with charges set to provide cost recovery. Total staff is about 400.

Glass and Ceramics is one of the areas in which ORF provides R&D and specialized services on a contract basis. ORF has developed and established expertise over three decades and is one of the leading organizations in this area in Canada.

Specialization include:

- Fine powder preparation and processing
- Sol-gel technology
- Forming and sintering
- Coating technologies (including plasma)
- Prototype development
- Material characterization
- Mechanical and thermal property measurement
- Composite preparation technology
- Optical fibre production
- Glass and ceramic-to-metal sealing
- Piezoelectric & ferroelectric ceramics
- Material processing in microgravity
- Technology transfer
- Systems consulting

7.9 Industry Associations

In addition to the well established Canadian Ceramic Society, a number of new industry associations have been formed in the last few years to promote the development, commercialization and use of advanced ceramics. These new industry associations are:

- The Advanced Materials Technology Unit of Queen's University (AMTU).
- The Canadian Advanced Industrial Materials Forum (CAIMF).
- The Canadian University-Industry Council on Advanced Ceramics (CUICAC).
- The Ontario Centre for Materials Research

7.9.1 The Advanced Materials Technology Unit (AMTU)

The major objective of the Advanced Materials Technology Unit (AMTU) is to promote, stimulate and enhance university-industry collaboration in all matters relating to Advanced Materials Technology. In order to facilitate this, AMTU provides a focal point within the university which allows industrial affiliates access to many different areas of departmental expertise, equipment and analytical techniques. There is synergism among the participating departments, which provides an interdisciplinary component to the solution of many of the tasks which arise. AMTU also provides access to the main and branch libraries of the university and the many services they provide to users.

The university participants in AMTU are: Departments of Metallurgical, Chemical, Mechanical and Electrical Engineering; Physics; Chemistry; Geology; and School of Business.

AMTU organizes theme conferences and evening seminars on topics relevant to the interests of its industrial affiliates. At present, there are 15 industrial affiliates.

Assisting industry in the development/use of advanced ceramics is a part of the overall activities in advanced materials. AMTU believes that the needs of industry are better served if the advantages of using advanced ceramics are put in the context of other competing materials such as composites, advanced metals and polymers. To this end, AMTU tries to provide a broad perspective in the development and use of advanced ceramics.

7.9.2 The Canadian Advanced Industrial Materials Forum

The Canadian Advanced Industrial Materials Forum (CAIMF) is federally incorporated as a non-profit organization and was actively sponsored by the Canadian Manufacturers Association. the concept of the organization was developed by a group of concerned people from industry, government and universities to meet challenges and opportunities facing Canadian industry in new materials and their impact on Canadian resource and manufacturing sectors.

The objectives of CAIMF are:

a. To provide a national focus for Advanced Industrial Materials (AIM) and, thereby,

b. to promote competitive development and use of AIM in all reasonable, lawful and proper ways;

c. to ensure strong, long-term linkages and communications between users, suppliers, designers, manufacturers and researchers related to AIM;

d. to provide a forum for the exchange of legally exchangeable information on all subjects of common interest to Members;

e. to collect, analyze and distribute design, performance, technical, statistical and other information related to AIM;

f. to make representation to government and other bodies on questions of common interest to the members with respect to AIM.

CAIMF expects to implement the following activities:

- Newsletter (bi-monthly)
- Directory
- Advisory service
- Seminars/workshops (quarterly)
- Automated information service
- Materials audit service
- Experimental seminars

In a recent meeting, CAIMF established a new Board of Directors. CAIMF has already attracted about 30 industrial members and has received financial assistance from DRIE to implement its programs.

CAIMF is expected to play an important role in sensitizing Canadian industry in the development and use of all advanced industrial materials including advanced ceramics.

7.9.3 The Canadian University-Industry Council on Advanced Ceramics

The Canadian University-Industry Council on Advanced Ceramics (CUICAC), was formed in June 1986 as a joint effort of Canadian universities and industry catalyzed by the Federal government, particularly the Department of Regional Industrial Expansion, Ottawa, and the National Science and Engineering Research Council, Ottawa. The latter is supporting CUICAC with a financial grant for a period of two years.

The objectives of CUICAC are:

- To promote, foster and focus university and industry activities in the field of Advanced Ceramics;
- to ensure, and contribute to, the establishment of national goals for Advanced Ceramics which incorporates research and development, manufacturing and technology, and market development;
- to promote a broader understanding of international activities in Advanced Ceramics in Canada;
- to promote the awareness of the Canadian achievements in Advanced Ceramics; and,
- to increase public awareness of the strategic importance of Advanced Ceramics.

CUICAC is administered by an elected Board of Directors and an elected President. It has three types of membership: university membership; industrial membership; and, associate membership. Currently membership is 8 universities, 43 industrial companies and one government agency.

CUICAC organizes at least three Workshops every year and publishes a Newsletter on a bi-monthly basis. CUICAC also promotes the initiation of pre-competitive research programs for the benefit of its members. At present it has organized a "superconductivity" consortium and is in the process of promoting a "non-destructive testing consortium".

CUICAC is establishing international linkages. It has signed an agreement with the Japan Fine Ceramics Association for cooperation in the exchange of technical information and other activities of mutual benefit. It is negotiating with the United States Ceramics Association (USACA) for a similar arrangement and hopes to negotiate agreements with European countries. CUICAC hopes to particiapte in setting up a nation-wide network of interested organizations in Canada to assist Canadian industry in the development and use of advanced ceramics.

7.9.4 Ontario Centre for Materials Research

The Ontario Centre for Materials Research (OCMR), is one of the seven "Centres of Excellence" set up by the Ontario provincial government in June 1987. With enabling funds from the provincial government, the Centre has been created to perform world class university research in materials in Canada. In this innovative venture, OCMR offers industry the opportunity to share the expertise and resources of universities by engaging in collaborative research programs. OCMR plans to supplement the provincial grants with contractual research projects from industry.

The production and use of materials is a major component of the economy of Ontario. Since the translation of basic scientific knowledge for the benefit of society is carried out through technology, OCMR aims to respond to the needs of Ontario industry in the following ways:

- By providing a multi-disciplinary environment in which world-quality long-term materials research will be undertaken in areas of strategic importance to Ontario's industries.

- By encouraging close, interactive relationships between the academic community and their industrial colleagues at all stages of product and process research and development.

- By educating and training personnel of high calibre in a variety of areas of direct value to the material industries of Ontario.

OCMR is a federally chartered incorporated body and is managed by a 16-member Board of Directors representing industry and university members. The present university membership comprises: McMaster University; Queen's University; University of Toronto; Waterloo University; University of Western Ontario. All the research programs sponsored by OCMR will be carried out in these institutions. The initial industrial support for the creation of OCMR has come from about 40 companies.

The Centre's research projects have been organized into five theme areas, each one involving researchers from more than one university. These areas are: Biomaterials; Microstructural optimization; Polymers and composites; Optoelectronic materials; and Interface science and technology.

The research on glass and ceramic materials pervades all the theme areas. Specific programs on glass and ceramics will be carried out under "microstructural optimization" theme. These activities are: development of new crystalline materials, joining of materials, new methods of synthesis, and metal matrix composites.

8. IMPACT OF ADVANCED CERAMICS ON CANADIAN INDUSTRY

8.1 General

As discussed earlier, advanced structural ceramics are being developed to meet the present and future needs of industry. Although the primary emphasis to date has been the heat engine industry, it is now recognized that, from a business point of view, the short term pay off will come from non-engine industrial sectors of the economy. In this section the impact of advanced ceramics on some Canadian industry sectors will be presented.

The Gross National Product of Canada for 1986 was $ 364.5 billion at 1981 prices. The components of GNP are shown in Figure 32. The manufacturing sector amounted to $ 71.12 billion (19.51%). The mining, oil & gas sector accounted for 5.78 %. The transportation & storage and communication sectors accounted for 4.47% and 2.95% respectively.

A breakdown of Canadian manufacturing industries in terms of employment and value of shipments for 1985 is given in Figure 33. The value of shipments by industry sectors where advanced ceramics can have impact are listed below:

Sector	% Shipment
Transportation Equipment	20.58
Petroleum Products & Coal	8.95
Pulp & paper	6.56
Primary metal	6.04
Electrical & Electronic Products	5.46
Fabricated Metal	5.2
Machinery	2.99
Non-metallic Mineral Products	2.28

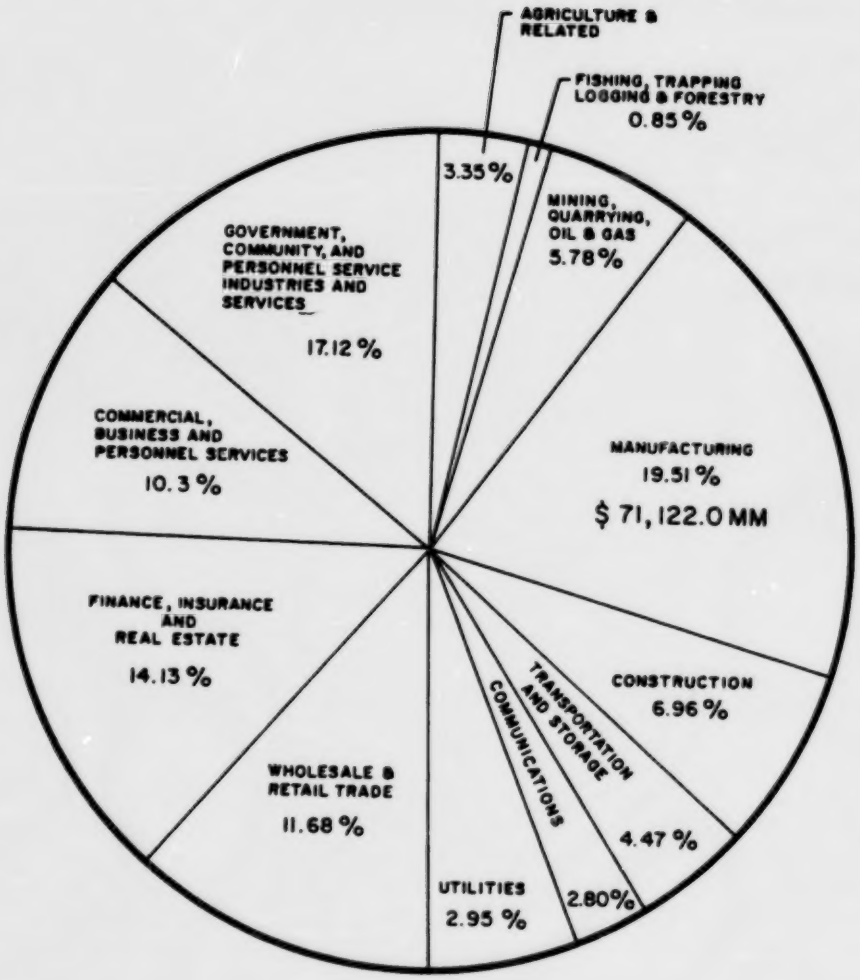
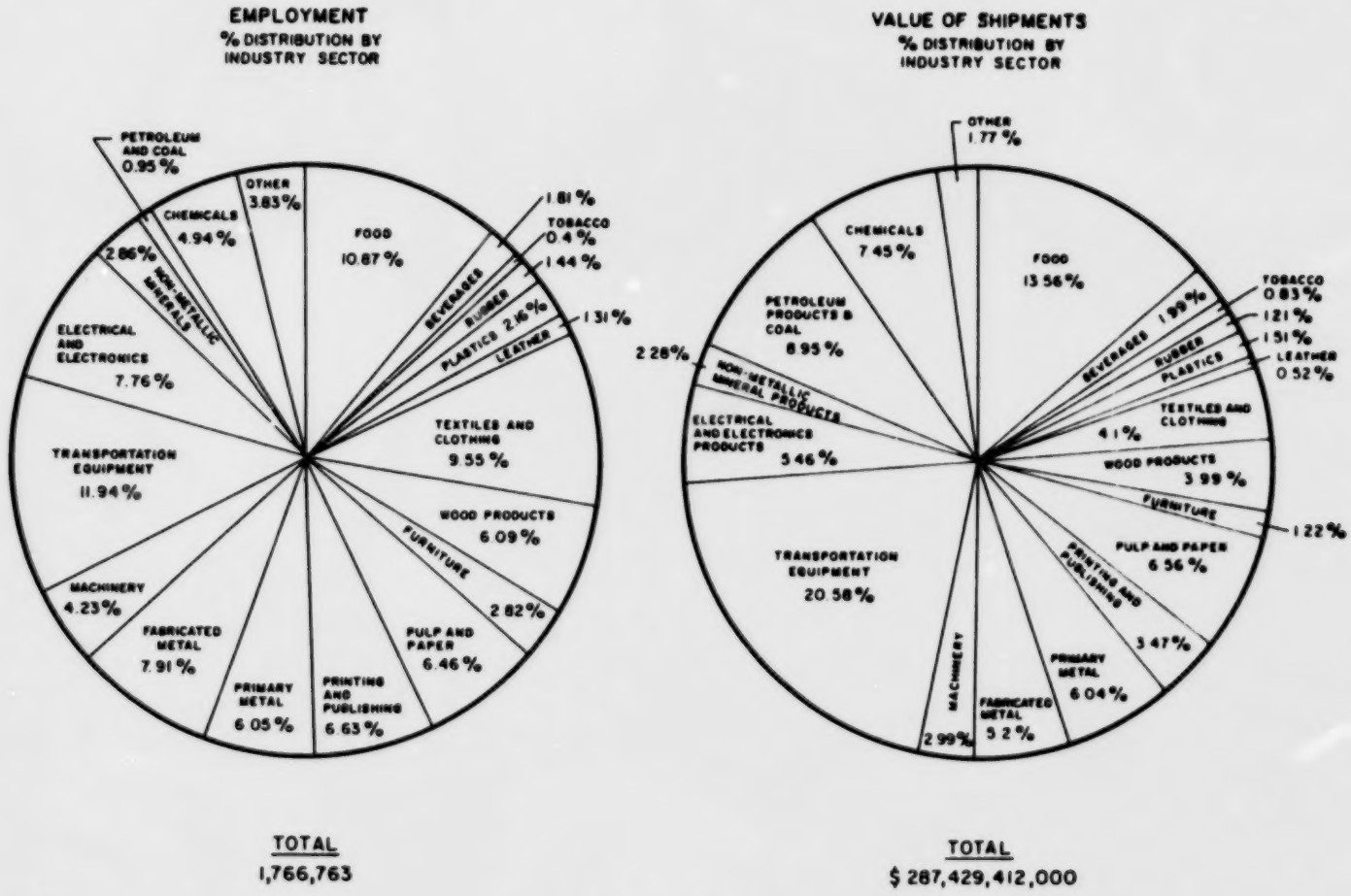


Figure 32. Gross National Product of Canada for 1986



SOURCE : STATISTICS CANADA

Figure 33. Employment and Shipment Data on Canadian Manufacturing Industries(1986)

In this study, the impacts of advanced ceramics on the following industrial sectors have been identified:

- Auto Parts Industry
- Mining & Mineral Processing Industry
- Pulp & Paper Industry
- Oil & Gas, and Petrochemical Industries
- Machinery and Equipment Industry

8.2 Auto Parts Industry

The Canadian motor vehicle parts industry comprises of three main segments. These are:

1. The captive plants of the major motor vehicle manufacturers.

2. Canadian subsidiaries of foreign-based (mainly U.S.) parts manufacturers.

3. Canadian-owned motor vehicle parts manufacturers.

The captive plants of the motor vehicle manufacturers tend to concentrate on the production of higher value-added parts such as engines and engine parts, transmission components, body stampings, and major trim parts. The foreign-owned parts manufacturers have tended to produce large, heavy stampings for frames, seats, steering and axle components, exhaust parts, and electrical and electronic parts. The Canadian-owned parts producers have tended to focus their activities on the production of heavy stamped parts, plastic trim parts, electrical assemblies, and miscellaneous engine, steering, axle, and suspension parts. 1985 shipments from the motor vehicle parts manufacturers were $13.2 billion.

Engine components are of special interest to advanced ceramics producers. In 1985, there were 38 plants classified by Statistics Canada as producers of motor vehicle engines and engine parts. These plants shipped $3.8 billion worth of products in 1985. Some of the major engine and parts producers are listed in Table 61.

The Canadian motor vehicle and parts industry is highly oriented to the needs of the U.S. market. Production of engines and engine parts is rationalized between the U.S. and Canada, with Canada producing the larger V6 and V8 engines and the U.S. producing the smaller V6 and 4-cylinder engines. Canada runs a significant deficit in trade in engine parts with the U.S. Canada also relies on imports for all of its small diesel engine requirements.

TABLE 61

Major Canadian Engine and Engine Parts Manufacturers

PLANTS	LOCATION	MAIN PRODUCTS
	Captive Plants	
American Motors (Canada) Inc. (now Chrysler Canada).	Sarnia	Engine blocks (to be closed in 1988)
Chrysler Canada	Etobicoke	Pistons, water pump bodies, transmission transfer cases
Ford Motor of Canada	Windsor(Essex) Windsor(Ensite #1) Windsor(Ensite #2)	V6 engines V8 engines Engine machinery and stampings; Iron & aluminum castings
General Motors of Canada	St.Catherines	Ferrous, non-ferrous engine castings
	St.Catharines	Forgings(transmission axle, engine parts)
	St.Catharines Windsor	V6 engines Transmissions
	Independent Producers	
TRW Canada,Thomson Products Div.	St.Catharines	Engine valves
Amcan Castings	Hamilton	Engine parts; castings
Kendan Manufacturing	Windsor	Disel engine parts
Court Industries	St.Catharines	Valve guides
Dominion Forge	Windsor	Engine parts
General Forge	Welland	Engine parts
CAE Industries	St.Catharines Welland	Engine parts

Increasingly, there has been a trend to world-wide sourcing of engines and engine parts for North American vehicles. This trend is a function of production rationalization decisions of the major auto manufacturers. For example, many of the engines installed in North American cars are built in Mexico, Brazil, and Taiwan where labour costs are much lower. These trends are expected to continue, as manufacturers seek to reduce their input costs.

Ceramics are of considerable interest to motor vehicle engine manufacturers. The ceramic properties of most advantage are wear resistance and thermal stability. The lower density of ceramics in comparison to metals is also of interest for some applications. In terms of motor vehicle engines, there are two distinct markets for ceramics. Passenger cars will use ceramics primarily for their wear resistance properties. The thermal resistance and lighter weight are of secondary interest. The applications of interest are valve train components and piston parts such as: valves, valve guides, valve seats, tappet faces, cam followers. Piston components such as piston crowns, wrist pins, and cylinder liners will be in less demand.

The utility vehicle market will use ceramic parts primarily for their thermal properties. It is expected that most of the engines for utility vehicles will be diesels. Ceramics offer promise of higher engine operating temperatures and thus increased efficiency. The major diesel engine opportunies for ceramics are:

- glow plugs, precombustion chambers
- piston crowns, piston rings and wrist pins
- cylinder liners
- valve train components
- exhaust port liners

Turbocharger rotors are a common opportunity for gasoline and diesel engines.

Most of the applications listed are still in the experimental stage of development. Simple components such as cam followers are the closest to full commercial development. Turbocharger rotors have been sold in limited commercial quantities for use in luxury and high performance cars. Heat management components have also been sold in limited commercial quantities. A recent forecast (*) predicts that significant growth in the use of ceramics in motor vehicle engines will not take place until the early 1990's. It is expected that the average passenger car might have only 0.5 kg of ceramic parts by 1990 and only 2.5 kg of ceramic parts by 1995. The tonnage of engine components made of different types of advanced structural ceramics is expected to increase from about 2690/year in 1990 to about 30,000/year in 1995(*).

(*) High-Tech Materials Alert. Interceram, No.5, p 68, 1987

To date Canadian auto parts manufacturers(*) have not showed much interest in the use of advanced ceramics. This is probably due to the present business climate re: advanced ceramics components for engines. Japan has a committed interest in this area. It has already built considerable infrastructure for manufacturing advanced structural ceramic components and the auto industries have invested heavily in R&D. Since Japanese auto companies have established manufacturing facilities in the U.S. and in Canada (and are likely to increase this commitment), it is likely that ceramic components will enter the North American market thus forcing the North American manufacturers to follow.

The North American auto industry is facing large production capacity problems in the next few years. With a new series of transplant assembly operations and joint ventures between domestic and foreign producers coming onstream, the North American car capacity is expected to outstrip sales by 4-5 million units by the early 1990's. With foreign automakers capturing an ever-increasing share of the market, it is likely that the Big Three North American producers - Chrysler, Ford and General Motors - will bear the brunt of the overcapacity crunch leading to rationalization, both in the U.S. and in Canada.

The $37 billion Canadian auto industry supporting 450,000 employees is also expected to be impacted in the rationalization process, more so because of the new car manufacturing capacity expected to be in place by 1990 as a result of Japanese and South Korean plant transplants, the joint ventures between General Motors of Canada Ltd., and Suzuki, and Chrysler's new plant in Bramlea, Ontario, as shown below:

Manufacturer & Location	Production Start	1990 Capacity (units)	Additional Potential Capacity
Honda, Alliston,Ont	1987	80,000	70,000
Toyota, Cambridge,Ont	1989	50,000	100,000
Hyundai, Bromont, Que	1989	100,000	-
Suzuki/GM, Ingersol,Ont	1989	200,000	-
Chrysler, Bramlea,Ont	1987	180,000	-

The Canadian auto parts industry - made of about 2000 companies employing 68,000 people - which shipped $11.9 billion worth of products in 1987, is also expected to undergo significant changes, particularly because of the Canada-United States free trade agreement which might

---

(*) Bombardier Inc., in Montreal, manufacturers of diese; engines for locomotives is interested in developing/using ceramic components and coatings in their engines.

lead to import of more auto parts from the Third World. Also, the Japanese branch plants in Canada are expected to continue to bring in parts from their suppiers in Japan. However, they are also expected to support setting up Canadian auto parts manufacturing by joint- venture between Japanese auto-parts manufacturers and Canadian enterprises to accommodate the just-in-time parts supply philosophy.

Another important change that is in progress in the North American auto-parts industry since the recession of 1982 is the mandate from the auto manufacturers to delegate more and more the design function and R&D to the parts manufacturers. As a result, there will be more cooperation between the auto manufacturers and parts suppliers in developing new auto parts and components. Canadian auto parts manufactures are already responding to these business methods.

In view of the present and impending changes due to the rationalization of the North American auto industry, and the new business relationhsip between the auto and auto parts manufacturers, it is difficult to predict/project the future of ceramic components. One possible scenario is based on the present interest/enthusiasm in Japan for developing and introducing ceramic components for engines. This is expected to continue because of technological achivements made to date as well as to recover huge R&D investments made so far. It is likely that the Japanese ceramic parts manufacturers will consider -at some future date - the feasibility of manufacturing the components in Canada if the volume and business climate are in favour. It is believed that the existence of advanced structural ceramics technology and capabilities in Canada will play an important role in the decision making process.

8.3 Mining and Minerals Processing Industry

The mining industry is an important component of the Canadian economy. In 1986, the value of the Canadian mineral production was about $16 billion. In a typical year, 80% of the production is exported and it amounts to 20% of Canada's total export earnings. Canada is among the leading producers of zinc, uranium, potash, nickel, asbestos, sulfur, gypsum, aluminium, cadmium, lead, copper, silver and iron ore. The industry directly employs 120,000 Canadians and is 70% owned by Canadians.

Broadly classified, Canada's mining and mineral processing industries shipped $15.5 billion worth of products in 1986. The industry comprises of the following major segments:

- Metal mines ($8,566.4 million)
- Non-metallic minerals ($2,668.8 million)
- Structural materials ($2,200.5 million)
- Coal ($1,716 million)

Processing of these materials into semi-finished and finished products added a further $11.3 billion to the value of output. In total, the primary metal industries shipped $16.97 billion worth of products in 1986, while the non-metallic minerals industries shipped $5.88 billion worth of products.

The major metal commodities and non-metallic minerals produced in Canada are listed in Table 62. The metals were produced from processing almost 300 million tonnes of ore.

Structural materials producers shipped $2.2 billion worth of stone, cement and related materials in 1986. Coal production totalled 57.8 million tonnes in 1986 for a value of $ 1.7 billion.

Metals production in Canada is dominated by a few large companies who operate mines across the country. Some of the major companies involved and their principal interests are:

Company	Products
Alcan	aluminum (from imported bauxite & alumina)
Noranda	gold, copper, zinc, lead, silver
Inco	nickel, copper, gold
Falconbridge	nickel, copper, zinc, gold
Cominco	copper, lead, zinc, gold, silver
Teck Corp	copper, gold, silver, molybdenum
Lac Minerals Ltd.	gold, silver
Int.Corona.Res.	gold
Placer-Dome Inc.	gold, silver
Rio Algom Ltd.	uranium, copper,potash
Denison Mines Ltd.	uranium, potash
Iron Ore Co.	iron ore
Wabush Mines Ltd.	iron ore
Eldorado Nuclear	uranium
Lornex Mining Corp.	copper, molybdenum
BP Canada Inc.	copper, zinc, gold

This list is not meant to be exhaustive. Because of the high cost of mine development, and the risks inherent in any individual project, there are extensive cross-holdings of ownership positions in companies and individual mines, making a comprehensive list difficult to produce.

Non-metallic minerals and stone products are produced by a more extensive group of companies. Some of the principal non-metallic mineral producers and their product concentrations are:

Company	Products
Rio Algom Ltd.	potash

TABLE 62

Major Metal and Non-Metallic Minerals Produced in Canada

Metallic Minerals

	1986 Production	
	Tonnes	$ '000
copper	768,224	1,567,938
iron ore	36,096,000	1,254,758
zinc	1,055,103	1,304,107
gold	104,655 (kg)	1,715,392
nickel	180,599	1,075,467
uranium	10,977	933,838
silver	1,219	310,102
lead	303,503	204,427
molybdenum	12,914	113,942
others		96,424
total		8,566,415

Non-Metallic Minerals

	1986 Production	
	Tonnes	$ '000
asbestos	640,000	300,536
gypsum	8,542,000	80,613
potash	6,969,000	579,022
quartz	2,437,000	42,814
salt	11,088,000	241,611
sulphur (all types)	7,528,000	994,068
others		250,283
total	40,130,000	2,668,790

Domtar Inc.(Sift Salt Dn)	salt
Denison Mines	potash
Potash Corp. of Sasketchewan	potash
Indusmin Inc	nephyline syenite, silica
Cassiar Asbestos	asbestos
Soc.de l'Amiante	asbestos
Domtar Inc (Const.Prod. Div)	gypsum
Canada Gypsum Co.	gypsum

Table 63 provides a listing of major operating mines in Canada in terms of their geographic distribution. As can be seen, the mining industry operates in all regions of Canada.

Stone production is very broadly based. Producers range in size from the major cement companies operating quarries producing severl hundred thousand tonnes per year to one and two-person operations producing a few hundred tonnes per year.

The major coal producing regions of Canada are located in western Canada, expecially British Columbia and Alberta. These provinces accounted for 80% of the tonnage of coal produced in Canada in 1986. Sasketchewan accounted for an additional 15% of the production. The principal Canadian producers are:

. Manalta Coal Ltd
. Fording Coal Ltd
. Denison Mines Ltd
. Teck Corporation
. Westar Mining Ltd
. Crowsnest Resources Ltd.
. Esso Resources Canada Inc

The western Canada mines produce bituminous, thermal and metallurgical grade coals and sub-bituminous and lignite coals for use in thermal power plants. Coal production in eastern Canada is restricted to relatively small operations in Nova Scotia. Cape Breton Development Corp. (DEVCO) operates thermal and metallurgical coal mines.

Material requirements for equipment used in the mining and minerals processing industry are characterized by the following:

. high abrasion and impact resistance

. high corrosion resistance

. high heat resistance

TABLE 63

Major Operating Mines in Canada
(Classified by Major Commodity Produced)

Type of Mine	B.C.	Alta.	Sask.	Man.	Ont.	Que.	N.B.	N.S.	P.E.I.	Nfld.	Yk.	N.W.T.	Total
Gold	6	-	1	2	18	17	-	1	-	2	1	4	52
Silver	2	-	-	-	2	1	-	-	-	-	1	1	7
Iron Ore	-	-	-	-	3	1	-	-	-	3	-	-	[illegible]
Copper	8	-	-	10	-	[illegible]	-	-	-	-	-	-	26
Lead	2	-	-	-	-	-	1	-	-	-	-	3	6
Zinc	-	-	-	1	3	-	-	-	-	-	1	1	6
Nickel	-	-	-	3	15	-	-	-	-	-	-	-	-
Uranium	-	-	3	-	4	-	-	-	-	-	-	-	7
Potash	-	-	10	-	-	-	1	-	-	-	-	-	11
Coal	7	8	4	-	-	-	1	3	-	-	-	-	23
Asbestos	2	-	-	-	-	3	-	-	-	1	-	-	6
Molybdenum	1	-	-	-	-	-	-	-	-	-	-	-	1
Talc	-	-	-	-	1	1	-	-	-	-	-	-	2
Silica	1	1	2	2	2	2	1	1	-	1	-	-	13
Nephyline Syenite	-	-	-	-	2	-	-	-	-	-	-	-	2
Barite	2	-	-	-	1	-	-	1	-	-	-	-	4
Niobium	-	-	-	-	-	1	-	-	-	-	-	-	1
Antimony	-	-	-	-	-	-	1	-	-	-	-	-	1
Tin	-	-	-	-	-	-	-	1	-	-	-	-	1
Tantalum & Lithium	-	-	-	1	-	-	-	-	-	-	-	-	1
Ilmenite	-	-	-	-	-	1	-	-	-	-	-	-	1
Mica	-	-	-	-	-	1	-	-	-	-	-	-	1
Graphite	-	-	-	-	1	-	-	-	-	-	-	-	1
Salt	-	2	3	-	6	1	1	3	-	-	-	-	16
Total	31	11	23	19	58	27	6	10	-	7	3	9	224

Abrasion resistance is required primarily in the initial mining process. Material must be drilled and blasted, loaded and transported to crushers, and crushed and screened to the desired sizes. All of these operations involve considerable wear and tear on the equipment used. Current materials used in these operations include cemented carbide drill bit inserts, cemented carbide and special heat-treated digging teeth, special heat treated steels for chutes, skips, etc., for conveying ore, and for crushing and grinding the ore.

The preparation of concentrates and the subsequent smelting and refining of the concentrates to recover the metals requires the use of corrosion and heat resistant materials. Most of the chemicals used in the processes are highly corrosive, as are the gases that are evolved. High temperatures are required to reduce the materials to the metallic state. Stainless and other types of alloy steels are used to construct the process equipment. These materials are subject to severe stress corrosion cracking and other problems.

Abrasion is the most significant equipment problem associated with non-metallic mineral production and coal production.

Ceramics can be (and are) used in many of the applications noted above. Some of the high potential application areas for metallic mineral production are:

- drill bits and digging teeth : require harder longer lasting materials.
- wear surfaces for materials handling equipment: more abrasion resistant materials are required.
- crushing and grinding equipment: ceramic grinding media could be used.
- roasting equipment: ceramic burner nozzles, ceramic heat exchanger elements, ceramic-lined stacks and gas filters, and ceramic-lined piping could be used.
- gas treatment equipment: ceramic heat exchanger elements, ceramic-lined tanks and pipes, ceramic catalyst supports.
- refinement equipment: ceramic piping.
- process control: ceramic-based sensors for control of all thermal, hydrometallurgical, and electro-metallurgical operations.

These applications are illustrated in Figure 34 in terms of the major processes employed in the mining and mineral industry.

Recently Nantel of Noranda Research (*) has delineated the material research opportunities for the mining industry. The following summary is based on his presentation.

The Mining and minerals industry has gone through some very difficult times from 1982 to 1986(*). Through productivity improvements and cost cutting, the industry is now ready to embark upon a new era. This new era will be filled with several fundamental technological changes. The industry believes that some new materials will be of great help in some specialty applications. The material needs can be discussed in terms of three specific activities: exploration, mining and milling of ores.

Exploration

Exploration is the very first step of mining activities and it is divided into two phases: reconnaissance and target investigation. These involve geological mapping, geophysical prospecting, geochemical surveys, prospect drilling, exploratory underground workings. If warranted, these activities are followed by ore-body delineation.

The industry spends over $200 million per year. It costs about $ 60-90 per meter for drilling costs. A significant reduction in cost would be a major advance for the industry. The most common types of bits are the surface and impregnated bits. Depending upon the ground being drilled through either bit type is used: in broken ground, the impregnated bits are used because there is less tendency to break the impure or synthetic diamonds or "bortz". The hard material in these applications needs to be able to withstand abrasion and some impact.

Development of new advanced materials (advanced ceramics and metal alloys) has been identified as a research opportunity.

Mining

Mining methods are broadly classified into two categories: Surface or Open Pit Mining and Underground Mining. A further distinction is made for soft and hard rock formations.

Material needs are associated with: drilling, continuous mining, transportation, tunnelling, raise boring etc.

(*)"Challenges and Uses for Advanced Ceramics in the Mining Industry,". Presented by Jacques Nantel, Manager, Mining Technology Division, Noranda Research Centre, Point Claire, Quebec., at the 6th CUICAC Workshop, Toronto, Ontario, February 25, 1988.

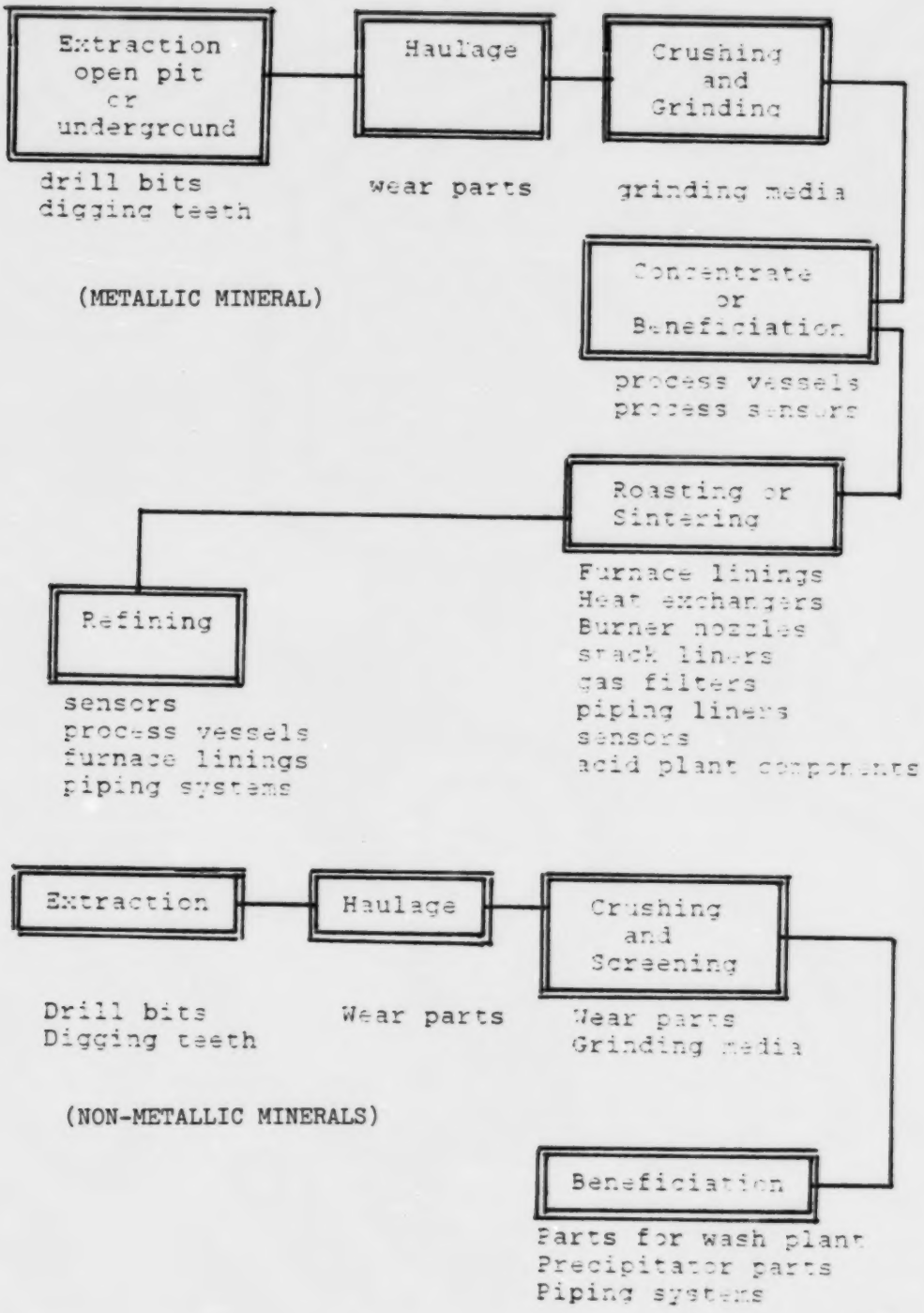


Figure 34. Material Requirements for Various Operations in Metal and Non-Metallic Mining and Mineral Beneficiation Operations

The drill-blast-muck cycle is at the heart of all hard rock mining. Holes of all sizes are drilled for the placement of explosives and then the rock is blasted. Holes vary from 22 to 200 mm in diamater and can reach 100 meters in length. The "bit" is the final interface between the drill and the rock formation. The mode of operation here is with percussion and some rotation, the rock cuttings being flushed with compressed air and water.

The needs of hard rock mining are particularly important. Two types of drilling bits are used at present: brazed bit and the button bit. The brazed bits are tungsten carbide inserts whereas button bits are cylindrical or spherical inserts embedded into the body of the bit. There appears to be room for advanced ceramic materials in this area. Important research is being carried out by Sandvik of Sweden. Canada should address this area.

Persussion drilling is becoming important. Development of new materials suitable for persussion drilling as well as continuous mining of hard rock offers another challenging material research and development opportunity. Specifically, the following opportunities have been identified:

. Hard materials for tunnel, raise and shaft boring machines

. Hard materials for continuous mining machines

Milling of Ores

For most base metal ores, the milling process is to transform the broken ore into a finely ground metallic concentrate which is then shipped for further processing by extractive metallurgical techniques. Milling involves communition or size reduction of ore by primary and secondary crushing, followed by grinding in mills. The material is made into a slurry and handled through pumps and piping systems. All these operations entail abrasion, particularly in slurry pumps, dewatering pumps, agitators, belt scrapers, centrifuge liners, chute liners etc.

Development of hard materials for the mineral processing sector of the mining operations has been identified as a research opportunity.

P.A. Verhey (*) has discussed the major savings and production efficiencies that could be achieved by using wear resistant ceramics in the mining and mineral beneficiation industry. High density alumina, oxide- and silicon nitride bonded- silicon carbide materials are being used with benefits accruing in terms of improved efficiencies and extended continuous service; value of ceramics is $1 million/year.

(*) P.A.Verhey, General Manager, Industrial Ceramics Division, Williams & Wilson Limited, Scarborough, Ontario, M1S 4K2.

Recently Advanced Materials Technology Unit of Queens's University (*) conducted an indepth study on the application of advanced materials in the mining industry, particularly for hard rock mining applications. The study concluded that:

- Cemented tungsten carbides remain favourable materials for percussion drilling and rock fracture in general.

- Monolithic ceramics and ceramic composites with fracture toughness of 15 MPa.m and flexure strengths in excess of 500 MPa can be advantageously used for high speed cutting, corrosive environments and insert technology.

- The relationship between the properties of ceramics suitable for inserts in steel should be examined and correlated with the properties of steel in order to reduce the possibility of compressive failure.

Discussion with some representative of the industry indicate that the industry will benefit significantly from using advanced ceramics. The industry is reluctant to embark upon a research program on the development of advanced ceramics. However, it will be very receptive to programs related to the performance of the materials in various operations in the mining and mineral beneficiation operations. These discussions also identified the absence of a suitable mechanism whereby the mining industry and the manufacturers of ceramics and/or R&D groups with knowledge and interest could meet to address the problems from a practical point of view.

According to Statistics Canada, the mining industry (including mines, quarries and oil wells) spent about $2.159 billion for machinery and equipment repair. No data is available idendifying the specific contribution due to abrasion and wear. Assuming it is about 20% of the total i.e., $ 430 million, one can see considerable economic benefit that can be achieved by using advanced ceramic materials.

(*) "Applications of Advanced Materials in the Mining Industry,". Report from Advanced Materials Technology Unit, Queen's University, Kingston, Ontario to Hard Rock Mining Research Limited.

8.4 Pulp and Paper Industry

Industry Size

The Canadian pulp and paper industry is one of the largest segments of the country's manufacturing base. In 1985, the industry shipped approximately $13.79 billion worth of products. The industry is composed of the following major segments:

- Pulp and paper mills producing pulp for conversion to paper in captive mills and for sale to third parties.
- Newsprint mills producing newsprint.
- Paperboard mills producing building and construction papers.

Conversion of these pulp and paper products into other finished products such as boxes, gift warp, greeting cards, stationary supplies, etc. added an additional $4.3 billion to the value of the output. In total, the pulp and paper and paper converting industry shipped approximately $18.1 billion worth of products in 1985.

Canadian mills produced approximately 20.5 million tonnes of pulp in 1985. This pulp was converted into approximately 14.3 million tonnnes of paper and paperboard, with approximately 6.2 million tonnes of pulp being sold on the open market. The major pulp and paper commodities shipped in 1985 were:

	'000 tonnes
Wood pulp (all kinds)	8,781
Newsprint	8,965
Other book & printing paper	2,167
Paperboard	2,318
Others	832
Total	23,063

The distribution of pulp and paper mills across Canada in 1987 is given in Table 64.

Producers

Pulp and paper manufacture is widely distributed across Canada. The major centres of production are British Columbia, Quebec and Ontario. Some of the principal producing companies are:

TABLE 64

List of Pulp and Paper Mills in Canada (1987)

Province	Paper Mills	Pulp Mills: Groundwood	Other Mechanical	Semichemical	Sulphite	Kraft	Other
British Columbia	10	12	1	-	1	18	-
Alberta	3	1	1	-	-	2	-
Saskatchewan	1	-	-	-	-	1	-
Manitoba	4	2	1	-	-	1	-
Ontario	35	13	4	2	5	9	1
Quebec	56	34	9	2	10	10	7
New Brunswick	7	6	1	2	2	3	-
Nova Scotia	5	4	1	-	3	1	-
Newfoundland	3	4	-	-	2	-	-
P.E.I.			none				
Yukon			none				
N.W.T.			none				
TOTAL	124	76	18	6	24	45	11

1. Noranda Forest Industries
2. MacMillan Bloedel Ltd.
3. Fraser Pulp and Paper
4. MacLaren Industries Ltd.
5. Northwood Pulp
6. Abitibi-Price Inc.
7. Canadian International Paper Inc.
8. Great Lakes Forest Products Ltd.
9. Consolidated-Bathurst Inc.
10. Bowater Inc.
11. Domtar Inc.
12. Reed Paper Inc.
13. Donahue Inc.
14. Canfor Inc.
15. Kruger Pulp & Paper
16. Irving Pulp & Paper
17. Tembec Inc.
18. B.C.Forest Products Inc.
19. Quebec and Ontario Paper Co.

Production Processes

Pulp and paper products are produced from cellulosic raw materials such as wood by mechanical and/or chemical processes. There are three main pulp manufacturing methods. They are:

- .Mechanical pulping: (including)
  - stone groundwood
  - refiner groundwood
  - pressurized groundwood
  - thermomechanical
  - defibrated and exploded
  - chemi-thermomechanical
- . Kraft (alkaline) pulping
- . Sulfite (acid) pulping

Mechanical pulping involves the comminution of wood fibres by rubbing either bolts of wood (short logs) against each other, against grinding stones, or by pressing wood chips aganist rotating ribbed steel plates. This latter process may operate at either atmospheric pressure or at elevated pressure. Additional heat and/or chemicals may also be used to soften the wood and speed the fiberization of the wood. Mechanical pulping methods do not remove the lignin from the wood fibre. Thus the cellulose fibres remain bound to the lignin and are not able to bind to each other. In the papermaking process fibre bonding is almost totally mechanical and the overall strength of the paper is less than that of paper produced from chemical pulping methods. The yield of pulp, however, is very high, generally over 90%.

The principal mechanical pulping processes are:

- Stone ground: Bolts of wood are ground to a fine mass by the action of large grinding stones. This is the primary form of pulp for low strength papers such as newsprint.

- Refiner pulps: Wood is reduced to small wood chips by large disc chippers, and then ground to a fine mass between steel grinding plates at atmospheric pressure.

- Thermomechanical & Chemi-thermomechanical pulps: Bolts of wood are chipped and then ground to a fine mass under heat and elevated pressure; chemicals are sometimes added to assist in the dissociation of the wood fibres.

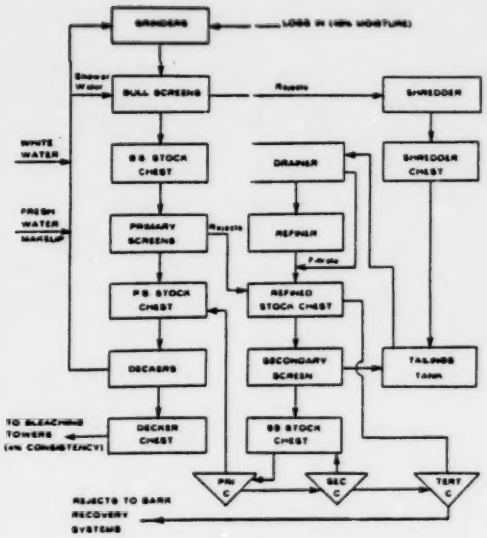
These pulping methods are illustrated in Figure 35.

Chemical pulping methods are based on the use of alkalies or acids to remove the lignin from the wood and thus free the cellulose fibres. During the papermaking process the cellulose fibres intertwine to form very strong mechanical bonds and weak hydrogen bonds. Chemical pulps are usually significantly stronger than mechanical pulps.

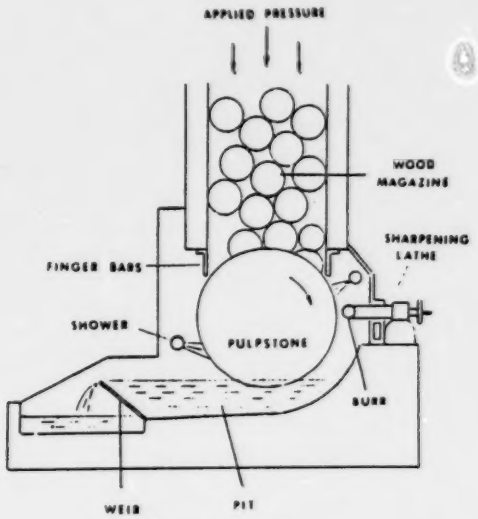
The principal chemical pulping methods are kraft or sulfate (alkaline) pulping and sulphite (acid) pulping. Bolts of wood are chipped and the chips placed in large digester tanks. The wood is then cooked under heat and pressure for a defined time period. Kraft pulping is based on the use of caustic soda and sodium sulfide and is the predominant form of chemical pulping in Canada. Sulfite pulping is based on the use of sulfurous acid and bisulfite ion to break down the lignin abd free the cellulose fibres. The cation associated with the bisulfite may be calcium, magnesium, sodium, or ammonium. Sulfite pulps are generally added to groundwood pulps for newsprint manufacture in order to increase the strength of the paper. Yields from chemical pulping processes range from approximately 50% to approximately 80% of the original wood volume. The general feature of the kraft and sulfite pulping processes are given in Figure 36. The processes may operate in either a batch or continuous mode.

Pulps may require bleaching by chlorine, chlorine dioxide, or peroxide to make them white. Both mechanical and chemical pulps can be bleached, although bleaching is generally only used with chemical pulps. The bleaching process may involve several bleaching and washing steps (usually four or five) until the desired degree of brightness is achieved, and may be conducted on either a batch or continuous basis.

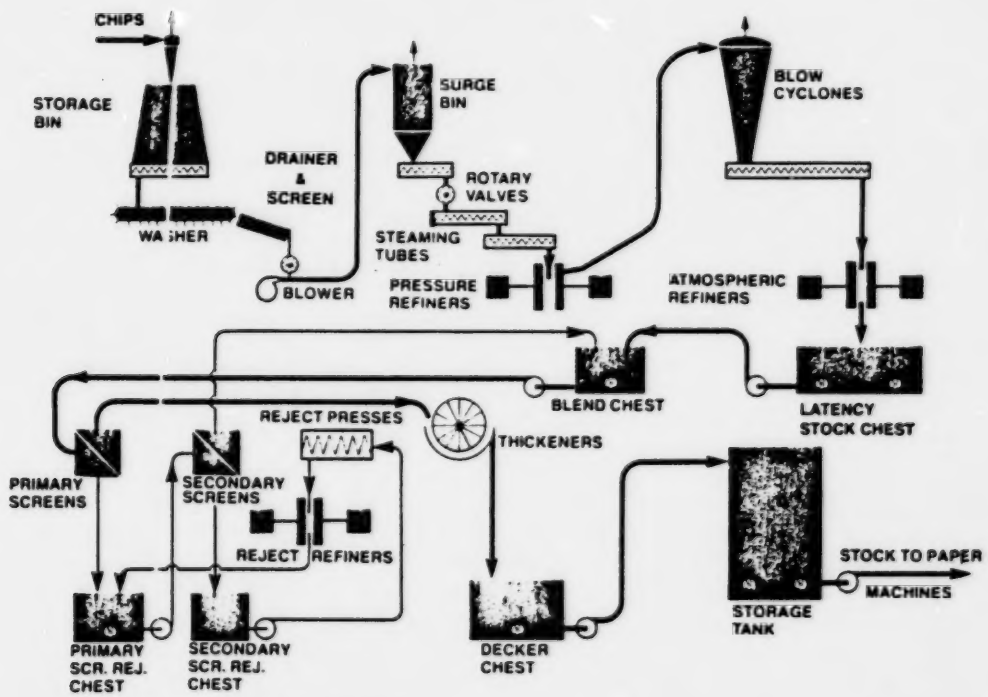
Wood pulp may be dried and sold to paper mills or used directly in the manufacture of paper. In either event, the pulp is mixed into a very thin slurry and spread in a thin layer onto a fine mesh wire.



Typical groundwood flow sequence



Arrangement of grinder.



Basic flow diagram for TMP process

Figure 35. Pulping Processes

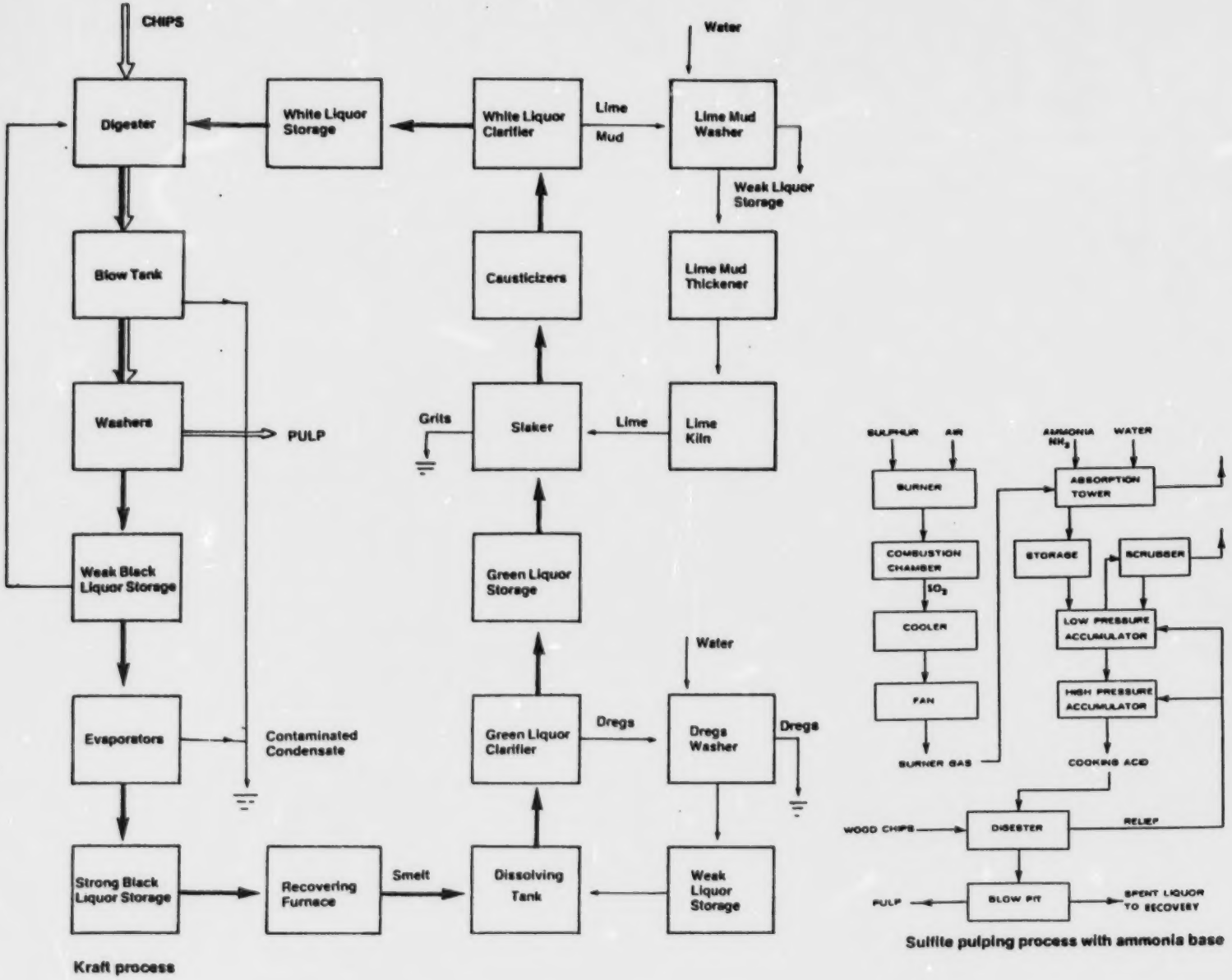


Figure 36. Kraft and Sulfite Pulping Processes

Typical paper machines can be very wide (over 300 inches) and operate at high speeds (2,000-3,000 ft/min). The water is removed by suction, pressing and drying in order to allow the paper to form by mechanical and hydrogen bonding of the cellulose fibres. Clay and other forms of fillers and coatings may be applied to increase the bulk of the paper and provide a glossy finish.

Equipment Materials

The principal requirements for pulp and paper machinery are abrasion and corrosion resistance. The chipping and disc refining processes impose severe abrasion loads on equipment. Chemical pulping methods impose severe corrosion loads on equipment. As a consequence, the most prevalent materials found in a pulp and paper mill are alloy and stainless steels such as 304, 309, 316L, 317L, etc., titanium and glass-lined tanks, and fibreglass tanks and piping systems. Stress corrosion cracking is a significant problem in chemical pulp mills and in paper mills.

Advanced ceramics can be used to provide abrasion resistant surfaces for pulp stones, chipping knives and refiner plates. Modern pulp stones are fabricated from sections of alumina or silicon carbide which are bolted together around a steel cylinder. Coatings of tungsten carbide and cemented carbide inserts are the most popular materials for chipping knives and refiner plates. The use of ceramic materials in chemical pulping and paper manufacture equipment is also gaining popularilty. The principal opportunities are:

- piping and tankage systems
- power and recovery boiler tubes and burner nozzles
- heat exchangers
- pump sleeves and valves
- parts for electrostatic precipitators, flue gas cleaners etc., exposed to acidic environments
- bearings
- showers for pulp washings
- suction rolls
- pulp screens and washers
- doctor blades and dewatering elements

The benefits to be gained by the use of advanced ceramics in the pulp & paper industry have been recently identified by Dr.Chaklader(*).

(*) Dr.A.C.D.Chaklader, Department of Materials & Metallurgical Engineering, University of British Columbia, Vancouver, B.C. Data obtained by discussions with Macmillan Bloedel Ltd., Vancouver. Personal communication.

With the exception of grinding plates for pulping, the bulk of the material needs in the pulp and paper industry are to withstand corrsive caustic environment in various process steps. It is understood that the pulp and paper industry is one of he most important customer for chemically resistant ceramics. In fact, the use of chemically resistant bricks as liners in pulp digesters actually made possible the widespread manufacture of sulfite pulps in North America, beginning in the early 1900's. These bricks were replaced by glazed tiles in the 1930's and have gained wide acceptance and, today, their place in pulp and paper mill operations has become firmly established. Carbon bricks are also used in both acid and alkaline conditions, except where strong and hot oxidizing conditions exist suc as hypochlorite and chlorine dioxide.

In general, the need and opportunities for advanced ceramics in the pulp and paper manufacturing operations arise out of the need to use corrosive resistant ceramics in: (i) pulp digesters; (ii) sulfite liquir accumulators;(iii) reactor spent acid tanks; (iv) lime kilns;(v) bleaching towers; and (vi) melt spouts for handling molten alkali (76% Na_2CO_3 . 21% Na-sulfite, 1% Na-sulfate, and 1% Na-hydroxide) at 800 - 850 C. Of these, the most severe requirements are placed by the last operation.

In addition to pulp tanks and digesters, the need for advanced ceramic parts/components were indicated in the following areas:

- Elbow chutes
- Screw conveyors
- Impellars
- Dust collectors
- Shafts and sleeves
- vacuum filtration equipment
- Cyclone linings
- Ash handling equipment
- Chain conveyor troughs
- Screw conveyor troughs

Recently Dr.C.Thomson(*) of the Pulp and Paper Research Institute reviewed the opportunities for advanced ceramics in the pulp and paper manufacturing operations. His conclusions confirm the foregoing opportunities. Dr.Thompson also indicated that the pulp and paper industry will not be interested in sponsoring R&D work oriented towards developing ceramic materials. He thought that they would be interested in working with the manufacturers of ceramics in the use of advanced ceramics in solving their material problems if a suitable infrastructure can be established e.g., funding mechanisms and R&D capabilities.

(*) Paper presented at the 6th CUICAC Workshop, Feb 25,1988, Toronto.

8.5 Oil & Gas and Petrochemical Industries

Industry Size

Canadian oil, natural gas and natural gas by-products production had a value of $18.3 billion in 1986. The petroleum industry consists of synthetic oil from tar sands, conventional oil producers, and natural gas and gas by-products producers. The industry can be divided into the non-integrated sector which concentrates on exploration and production; and the integrated sector, which both produces crude petroleum and refines the crude into usable products. The non-integrated sector is generally comprised of smaller companies and number several hundred. The integrated companies are generally large multinational firms. They include such companies as:

- Petro Canada
- Texaco
- Imperial Oil
- Shell Oil
- Suncor
- Husky Oil
- Ultramar Canada

A list of operating refineries is given in Table 65.

Production Processes

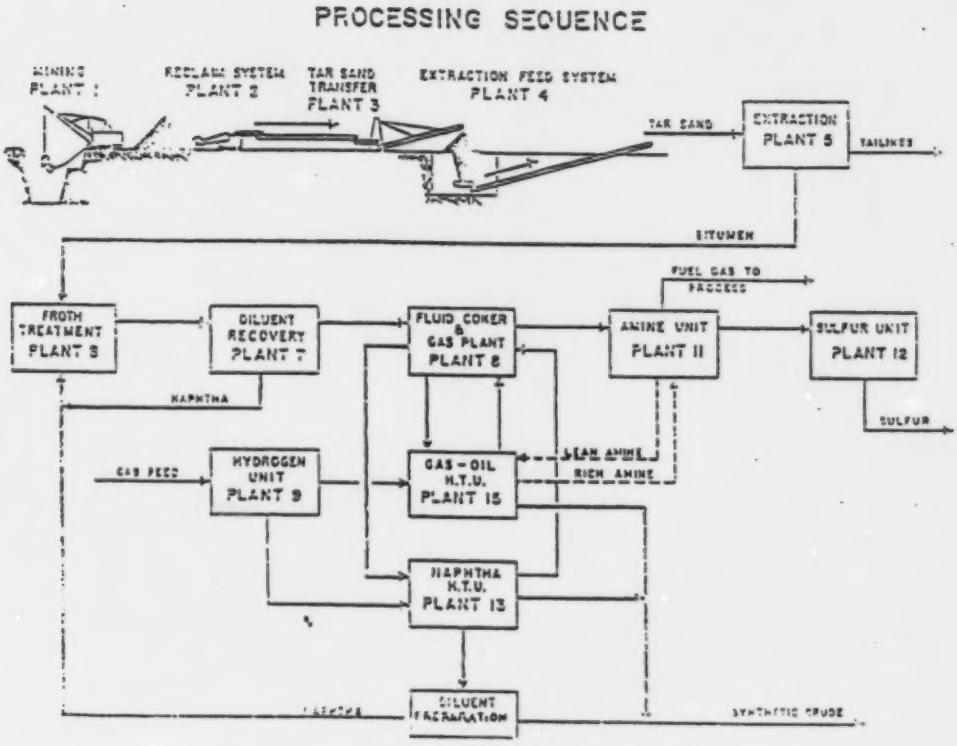
Synthetic oil production is actually a form of open pit mining. Tar sands are recovered by very large drag line and bucket wheel excavators and moved to a processing plant. In the processing plant the tar sands are treated with water and heat to separate the bitumen from the sand. The resulting bitumen is very viscous. It is subjected to chemical processes to remove sulfur and upgrade the oil to a more free-flowing product. The synthetic crude oil is then processed in conventional refineries. The overall process imposes severe abrasion and corrosion requirements on process equipment due to the extremely abrasive nature of the tar sands and the very high sulfur content of the bitumen. Figure 37 illustrates the processes employed at the Syncrude and Suncor tar sands plants in Alberta.

Conventional crude and natural gas production involves the drilling of wells using standard oil drilling equipment. The crude oil or natural gas is recovered at the well head and piped to processing plants for sulfur removal. Natural gas processing plants may also remove the higher carbon fractions of the gas stream, leaving only methane. Both crude oil and natural gas and gas co-products such as ethane may be subsequently converted into petrochemical products such as plastic resins.

TABLE 65

Operating Refineries in Canada (1987)

PROVINCE	COMPANY	CAPACITY (bbl/day)
British Columbia	Chevron Canada, Burnaby	36,000
	Esso Petroleum, Port Moody	40,700
	Husky Oil, Prince George	10,000
	Petro Canada, Taylor	17,000
	Shell Canada	24,000
Alberta	Esso Petroleum, Edmonton	165,500
	Husky Oil, Lloydminister	25,000
	Petro Canada, Edmonton	125,000
	Shell Canada, Fort Saskatchewan	50,320
	Turbo Resources, Balzac	30,000
Saskatchewn	Consumers Co-operative, Regina	47,000
	Petro Canada, Moose Jaw	14,000
Ontario	Esso Petroleum, Sarnia	126,100
	Petro Canada, Oakville	85,000
	Petro Canada, Clarkson	65,000
	Petrosar, Corunna	170,000
	Shell Canada, Corunna	74,000
	Suncor, Sarnia	90,000
	Texaco Canada, Nanticoke	95,000
Quebec	Petro Canada, Montreal	95,000
	Shell Canada, Montreal	120,000
	Ultramar Canada, St. Romauld	110,000
New Brunswick	Irving Oil, St. John	250,000
Nova Scotia	Esso Petroleum, Dartmouth	84,000
	Texaco Canada, Dartmouth	20,500
New Foundland	Haifa Oil, Come-by-Chance (in operation in 1988)	200,000
N.W.T.	Esso Petroleum, Norman Wells	3,000



Syncrude Plant

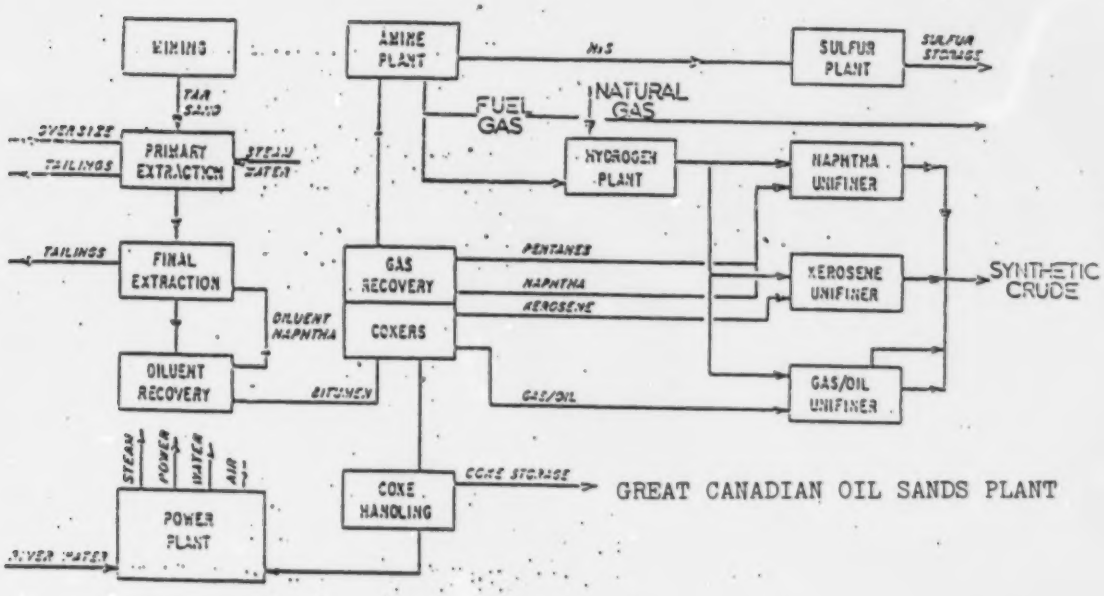


Figure 37 Process Sequence at Syncrude and Great Canadian Oil Sands Plants

Process equipment for oil and gas production and processing is generally based on the use of carbon, alloy, and stainless steels, and the use of glass-lined and fiberglass vessels. Abrasion and corrosion are the most significant problems faced by the equipment. Heat resistance is also of concern for some high temperature processing operations.

Petrochemical manufacture is concentrated in Alberta and in Ontario, especially the region around Sarnia. The Alberta petrochemical plants are generally based on the use of natural gas and/or the higher carbon fractions (ethane, propane, butane) of natural gas streams as feedstocks. The Sarnia petrochemical plants rely on the use of crude oil and naptha, as well as natural gas feedstock. There is also a petrochemical complex in Montreal, which is based on the use of naptha and refinery by-products as feedstocks.

Petrochemical production in Canada is concentrated in the basic resins such as polyethylene, polyvinyl chloride, polystyrene, and polypropylene. In 1986, production of thermoplastic resins was as follows:

	'000 tonnes
Polyethylene	
Low density	887
High density	242
Polyvinyl chloride	300
Polystyrene	146
Polypropylene	133
ABS	40

Production processes employed in petrochemical manufacture resemble those used in oil refining. Plants are quite large, and operate at high temperatures and pressures. Many of the raw materials and intermediate compounds used in petrochemical manufacture are highly corrosive, or are sensitive to trace elements of iron etc. Glass-lined vessels are often employed as the reaction vessels to overcome this lattter problem.

Opportunities for Advanced Ceramics

Several opportunities exist for the use of advanced ceramics in conventional oil and gas production and processing. Abrasion and impact resistant ceramic materials can replace dismonds in drill bits.

Corrosion resistant materials are required for protection against attack by sulfur compounds during drilling and during gas treatment. Ceramics can be used as catalyst supports and for corrosion resistance during the refining process and during petrochemical manufacture e.g., pump and valve seal faces, heat exchangers, and sensors.

The limitations on the use of ceramics relate to the availability of suitable sized equipment, chemical compatibility and cost. The principal application areas for advanced ceramics are shown in Figure 38.

R.B. Heimann of the Alberta Research Council(*) has identified the following specific problems in the Alberta oil and gas industry which provide opportunities for the use of advanced ceramics.

Company	Problem Area
Suncor	Coating of slurry and dike lines from extraction plant to prevent wear due to processing of abrasive oil sands in extremely cold climate.
Syncrude	Need for equipment that lasts a long time but requires minimal downtime when being replaced. Lubrication of large bearings in drag lines/ bucket wheels. Hardfacing and/or plasma spray coating of centrifuge bowls abraded by oil sands.
ESSO	Corrosion/erosion problems of pipelines in saltwater/hydrocarbon environment. Severe problems in very sour wells. Corrosion of steel pipe by deposition of raw sulfur.
Shell Canada	Materials evaluation in different environment, i.e., carbon dioxide from enhanced oil recovery and from source well environment with or without hydrogen sulfide. Corrosion by methanol and drilling mud. Fracture mechanics of drill pipe.
Petrocan	Corrosion by chloride in crude oil units. Fouling in heat exchangers by deposition of ammonium chloride that becomes corrosive at higher temperatures. Phosphate-containing pipeline corrosion inhibitors cause severe pitting in heat exchanger tubes.

(*) Robert B. Heimann, Manager, Materials Section, Industrial Technologies Department, Alberta Research Council, Calgary, Alberta, T6H 5X2. (Personal Communication)

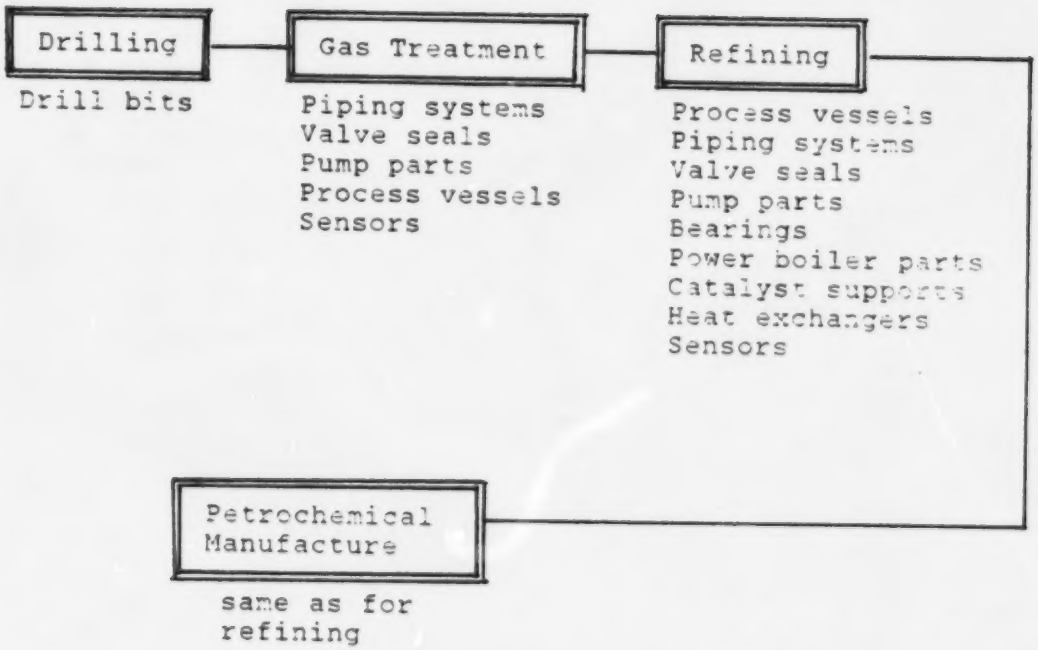


Figure 38. Possible Application Areas for Advanced Ceramics in Oil and Gas and Petrochemical Indutries

	In debutanizer units, trapped water in non-accessible parts leads to corrosion of exchanger trays. In catalytic crackers, erosion and heat, combined with high flow velocities, requires hard-facing with refractory materials.
	In cyclones and turboexpanders erosion of the blades takes place by particulates in the gas stream.
Aquitaine	Corrosion problems based on deposition of raw sulfur in steel pipe.

The Advanced Industrial Materials Task Force of the Alberta Research Council has addressed the materials problems encountered in the oil and gas production industry and has attributed these problems essentially to corrosion and mechanical wear. Because of cost considerations, carbon steel or low alloy steel is used even in extremely severe environments. Any new material that can replace the present materials has to provide significant cost-benefit before it is accepted by industry. The Task Force has identified the benefits to be gained by the use of plasma deposited advanced ceramic coatings on carbon steel and low alloy steel, particularly to increase the service life of downhole tools and production equipment by preventive maintenance. The combination of a wide variety of refractory oxides and carbides, often applied together with a metallic binder matrix to produce composite cermet coatings are expected to yield surfaces whose properties include thermal resistance to 3500 C, wear resistance up to 100 RC, high corrosion resistance and self-lubrication, depending upon the composition chosen.

8.6 Machinery and Equipment Industry

The Canadian machinery and equipment industry comprises of the following major segments:

- power boiler and heat exchanger industry
- metal dies, moulds and patterns industry
- machine shop industry
- metal valve industry
- machinery industry:
  - agricultural equipment
  - commercial refrigeration equipment
  - compressors, pumps, & industrial fans
  - construction and mining machinery
  - saw mill and woodworking machinery
  - turbine & power transmission equipment
  - other machinery & equipment industries

These industries shipped over $11.5 billion worth of products in 1985 from over 400 plants.

The Canadian industry is characterized by a large number of small plants. This industry structure imposes a number of constraints on Canadian companies such as lack of funds for R&D, market development, equipment acquisition, etc.; lack of technically trained staff; and short production runs. These constraints have tended to result in the development of two distinct industry segments: (i) those companies primarily serving the domestic markets with relatively standard products; and (ii) those companies serving international markets with highly specialized machinery and equipment.

The use of advanced ceramics in the machinery and equipment industry is presently restricted to cutting tools. The principal cutting tool materials and their applications are listed in Table 66. Market data on ceramic cutting tool use in Canada are generally not available. In the U.S. the cutting tool market (all types) is currently estimated at approximately $US 1 billion per year. The Canadian market is estimated to represent approximately 5% of the U.S. market, based on the relative sizes of the machinery and equipment in each country. Data on Canadian imports of metalworking tools indicate the following:

($ '000)

	1985	1986	1987
WC tools for metalworking	$15,537	$22,401	$19,824
Drills, taps, bits for metalworking machinery, primarily High Speed Steel	22,235	24,599	23,560
Diamond point metalworking lathe tools	14	17	NA

(Source: Statistics Canada)

TABLE 66

Typical Cutting Tool Materials and Their Applications

MATERIALS	APPLICATIONS
Tungsten carbide(WC-Co) and other cemented carbides	General purpose machining of all metals
Aluminum oxide (Al_2O_3)	Cast iron machining; High speed finishing operations for steel (light feed rates, shallow depth of cut).
Al_2O_3 - TiC composites	High speed machining of cast iron; Rough machining of superalloys; Turning and milling applications for most metals.
Al_2O_3 - SiC(w) composites	Aerospace alloy rough machining; Very low speed ferrous alloy machining
Si_3N_4	Gray cast iron machining
Si_3N_4- Y_2O_3- TiC -Al_2O_3 composites	Steel machining; Super alloy machining.
Diamond (single crystal)	Lapping of non-ferrous materials
Polycrystalline diamond in Coo-WC or steel substrate	Machining of non-ferrous abrasive materials such as high Si-Al alloys
Cubic Boron Nitride (CBN)	Ferrous alloys above 45 R_c Superalloys above 35R_c
Ceramic coated cutting tools	General ferrous and non-ferrous machining

8.7 Advanced Ceramics Needs and Requirements of Canadian Industry

The advanced ceramics needs of Canadian industry can be grouped into the following categories:

- Needs of Hi-Tech industries
- Needs of Automotive & Aerospace industry
- Needs of Primary industries

8.7.1 Needs of Hi-Tech Industries

In terms of size and growth, high technology industries are usually divided into electronics and all other high-tech industries such as computers, robots, office information & data processing etc. The electronics industry is by far the largest user of advanced ceramics at present consuming about 75% of all advanced ceramics. The market is growing at about 15-20 per cent per year.

At present, almost all the ceramic requirements of the Canadian electronics industry are being met by imported components and materials technology, the exception being the capacitor product lines manufactured by Murata Erie. To date, Japanese companies (e.g., Kyocera) dominate the world markets and are aggressively developing new materials and materials technologies to meet future needs.

Canadian electronics industry is expected to grow substantially in the coming decades and its materials needs are expected to be met by imported components. Nevertheless, opportunities exist for Canadian advanced electronics ceramics manufacturers (present and new) to take advantage of the growing market. These opportunities, however, will be "niche" markets suitable for small-to-medium size companies.

Canada has a relatively strong R&D base in functional ceramics in general and electronics ceramics in particular. Excellent expertise and facilities exist in Canadian universities and federal government laboratories. These could be harnessed to assist existing industrial companies to grow, and to promote the creation of new companies.

8.7.2 Needs of Automotive and Aerospace Industries

The Canadian automotive industry is now dominated by the American manufacturers: General Motors, Ford, and Chrysler. Japanese companies, which are now establishing a foot-hold in Canada are expected to play an important role in the coming decades. The South Korean Company Hyundai is also expected to influence the market place.

To date the North American manufacturers of automobiles have not shown much interest in the development and/use of advanced structural ceramics; bulk of the R&D has been done by ceramics manufacturers. However, interest by North American auto parts manufacturers in ceramics is incresing as indicated by the formation of industry consortia e.g., Norton-TRW, GTE-Eaton, and Ford-Ceradyne.

The growth in the use of advanced structural ceramics components in automobiles is expected to be influenced largely by the Japanese developments. Japanese manufacturers have already introduced a number of auto components and are expected to continue this trend. The respone of the North American auto manufacturers is not clear. Since all these manufacturers have business relationships with Japanese companies, it is likely that their future decisions will be influenced by the success with which Japanese ceramic industries solve the technology/ reliability/cost problems.

Industry consensus indicates that the growth in the consumption of advanced structural ceramics in gasoline engines will be slower than the early projections. The use of ceramic components in diesel engines is expected to grow at a faster rate, however, because of the technological advantages in terms of energy efficiency and the possibility of eliminating cooling systems.

To date the Canadian auto parts manufacturers have shown no interest in the development of advanced structural ceramics largely because they have not received positive signals from the North American auto manufacturers. This might change. Japanese government and industry are examining the business opportunities in Canada for participating in the manufacture of advanced ceramics(*). Canada has a number of advantages which are expected to play an important role e.g., inexpensive energy sources, extensive R&D capabilities, technical manpower and industry base. These advantages are expected to have positive influence in attracting the Japanese industry to Canada. Advantages notwithstanding, the future developments will largely be influenced by: (i) the response of Canadian industry, particularly by the Canadian auto parts manufacturers; and (ii) the ability of the canadian advanced ceramics industry to participate in this activity.

Although Canada has an advanced structural ceramics industry base it is relatively small. In moniolithic ceramics, the industry base is very small, however, in the coatings field it is susstantial. The development of advanced ceramic components for automotive applications involves a complex set of activities as shown in Figure 39. Although the development and manufacture of ceramic components is important, it is only one of the activities in a series of activities such as design

---

(*) Personal communication. T.Iwasaki & Associates. Suite 409, 107 Bloor Street W. Toronto. (Tel:416-927-7333)

To date the North American manufacturers of automobiles have not shown much interest in the development and/use of advanced structural ceramics; bulk of the R&D has been done by ceramics manufacturers. However, interest by North American auto parts manufacturers in ceramics is incresing as indicated by the formation of industry consortia e.g., Norton-TRW, GTE-Eaton, and Ford-Ceradyne.

The growth in the use of advanced structural ceramics components in automobiles is expected to be influenced largely by the Japanese developments. Japanese manufacturers have already introduced a number of auto components and are expected to continue this trend. The respone of the North American auto manufacturers is not clear. Since all these manufacturers have business relationships with Japanese companies, it is likely that their future decisions will be influenced by the success with which Japanese ceramic industries solve the technology/ reliability/cost problems.

Industry consensus is that the growth in the consumption of advanced structural ceramics in gasoline engines will be slower than the early projections. The use of ceramic components in diesel engines is expected to grow at a faster rate, however, because of the technological advantages in terms of energy efficiency and the possibility of eliminating cooling systems.

To date the Canadian auto parts manufacturers have shown no interest in the development of advanced structural ceramics largely because they have not received positive signals from the North American auto manufacturers. This might change. Japanese government and industry are examining the business opportunities in Canada for participating in the manufacture of advanced ceramics(*). Canada has a number of advantages which are expected to play an important role e.g., inexpensive energy sources, extensive R&D capabilities, technical manpower and industry base. These advantages are expected to have positive influence in attracting the Japanese industry to Canada. Advantages notwithstanding, the future developments will largely be influenced by: (i) the response of Canadian industry, particularly by the Canadian auto parts manufacturers; and (ii) the ability of the canadian advanced ceramics industry to participate in this activity.

Although Canada has an advanced structural ceramics industry base it is relatively small. In moniolithic ceramics, the industry base is very small, however, in the coatings field it is substantial. The development of advanced ceramic components for automotive applications involves a complex set of activities as shown in Figure 39. Although the development and manufacture of ceramic components is important, it is only one of the activities in a series of activities such as design

---

(*) Personal communication. T.Iwasaki & Associates. Suite 409, 107 Bloor Street W. Toronto. (Tel:416-927-7333)

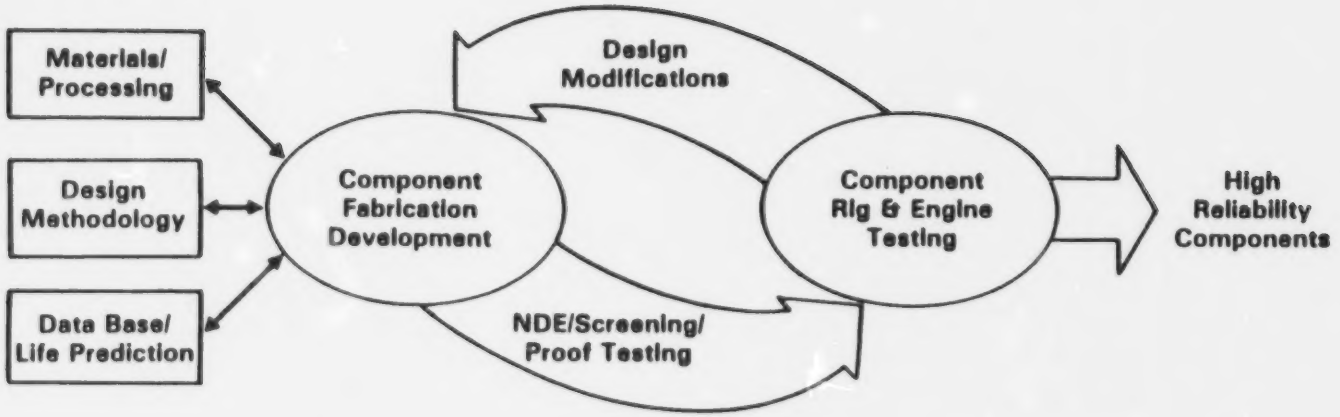


Figure 39. Methodology in Introducing Advanced Ceramic Technology into Engine Component Development and Testing Programs

development, data base/life prediction, non-destructive testing, component rig and engine testing. It is clear that successful development and commercializtion involves bringing together all these capabilities as well as large financial commitments.

As pointed out in Section 7, Canada has all the technological capabilities required to undertake the foregoing tasks. However, a national commitment is required by both the industry sectors and government. It is believed that a positive climate exists for the Japanese companies to locate manufacturing plants in Canada; and that the future depends on the leadership shown by industry and government. In Japan, the laboratories run by the Ministry of International Trade and Industry (MITI) are used by industry to complement their R&D effort. Also, in Japan government support and commitment to industry is looked upon very favourably. Hence, it is to Canada's advantage to focus attention to the expertise and excellent facilities available in the government laboratories and link them with industrtial capabilities as an "inducement" to attract investment in advanced ceramic industry.

In the Aerospace sector, plasma coatings are already used in jet engines and Canada has a well established industrial capability in this this area. Nevertheless, the companies are small and need outside R&D assistance to expand their technology base. Here again the expertise and facilities available at universities and government laboratories could be used to enhance Canadian industrial capabilities.

Monolithic ceramics are not expected to find applications in the aerospace industry (e.g., jet engines) at least until the year 2000 because of reliability problems. It is likely that advanced ceramic composities that are being developed may supplant monolithic ceramics by that time.

8.7.3 Needs of Primary Industries

It is now recognized that the good wear/abrasion/corrosion resistance properties of the first generation advanced structural ceramics can be used to improve efficiency and productivity in a number of industrial sectors such as: Mining and Mineral Processing, Pulp and Paper, Oil & Gas, Petrochemicals, Machinery & Equipment manufacture. Both Japan and U.S. are active in taking advantage of these opportunities.

From a Canadian perspective, the developments in the U.S. are perhaps the most significant because of the close interaction between the two economies. In the U.S. both levels of government i.e., federal and state, are implementing new initiatives designed to assist and promote industry in the development and commercialization of advanced ceramics. U.S. industry is expanding its commitment not only by

expanding in-house R&D activities but also by initiating vertical integration in the market place, by forming joint ventures, and by promoting and participating in univeristy-industry R&D consortia and industry associations. These government-industry commitments are expected to result in a rapid growth, both in the manufacture of advanced ceramics and their use by other industrial sectors to gain improvments in efficiency and productivity.

These developments in the U.S. are expected to have significant impact on Canadian industry. The user sectors will come under increased pressure to adopt new technologies based on advanced ceramics to improve their competitive position vis-a-vis U.S. industry. This is particularly critical because of the impending Canada-U.S. free trade agreement.

The Canadian industry is aware of these issues i.e., the benefits to be gained by the use of advanced ceramics in improving efficiency and productivity as a means of improving their international competitive position. Indeed, discussions with representatives of Mining & Mineral Processing Industry, Pulp & Paper Industry, Oil & Gas and Petrochemical Industry, and Machinery & Equipment Industry indicate their keen awarness and interest in the use of advanced ceramics in their respective industries. Translating this interest into positive R&D activities require some innovative approaches.

The Canadian user industries, in general, find it difficult to invest their limited R&D resources in the development of advanced ceramics. They feel that this is the responsibility of ceramics manufacturers. However, they have expressed positive interest in participating in specific component evaluation R&D which can contribute to improvements in efficiency and/or productivity in their operations.

One of the important criteria used by the user idustries in deciding new materials is "reliability" of the component in terms of performance and life expectancy. For example, in the oil refinery and petrochemical manufacturing operations, plant shut down cost varies in the range $ 1.5 to $ 3 million per day. Similar high down-time costs exist in almost all the user sectors. Hence, it is easy to understand the reluctance of these industries to use materials/components whose reliability is not well established.

Whereas extensive information exists on the processing of advanced ceramics and their properties, data on their performance in specific industrial applications - particularly reliability parameters- are hard to come by. Because reliable data can be obtained only from experiments designed to simulate operating conditions, accumulation of data is time consuming and expensive. When this is combined with the fact that the behaviour of test specimens depends to a large extent on

a large number of variables such as starting powders, fabrication and densification processes used, surface damage, applied stress levels and environmental exposure, the complexity of the problem becomes immense.

The relationships between major work elements required to establish ceramic component reliability for any specific industrial application is shown in Figure 40. This approach is well established in the U.S. and has been used for establishing reliability parameters for a number of applications e.g., heat engines, cutting tools and heat exchangers.

It is clear that substantial R&D infrastructure and financial expenditures are required to establish "reliability" of ceramic components. More importantly, the activities cut across a broad spectrum of disciplines and capabilities. The advanced ceramics manufacturers, by themselves, find it difficult to justify R&D expenditures required to satisfy specific requirements of user sector industries. In Canada this is all the more difficult because most of the companies in the advanced structural ceramics sector are relatively small. Also, many of the companies are new enterprises and already have too many demands on their limited R&D resources. Another important barrier is the very low R&D resources available in the Canadian manufacturing sector e.g., fully 70 per cent of manufacturers in Ontario - which accounts for the bulk of Canadian manufactured products- have no in-house engineering and/or scientific staff.

One option open to Canadian industry is to form "consortia" i.e., joint activity between the Canadian advanced structural ceramics manufacturers and user sector industries. The required technology infrastructure can be assembled by bringing together the excellent capabilities, expertise and facilities that already exist in industry, universities, and government laboratories.

Although Canadian universities have substantial scientific and technological resources related to the development and evaluation of advanced ceramic components, they are not geared to meet the time constraints imposed by industry requirements because of their dependence on graduate students and the commitments of professors to academic requirements. Nevertheless, their considerable capabilities can be harnessed to provide the required assistance.

At present there is a vacuum in leadership to bring together Canadian industry and the considerable scientific and technical capabilities that already exist. This vacuum can be filled by the government. The government laboratories with their established expertise and facilities could be used to provide focussed response to meet industry needs.

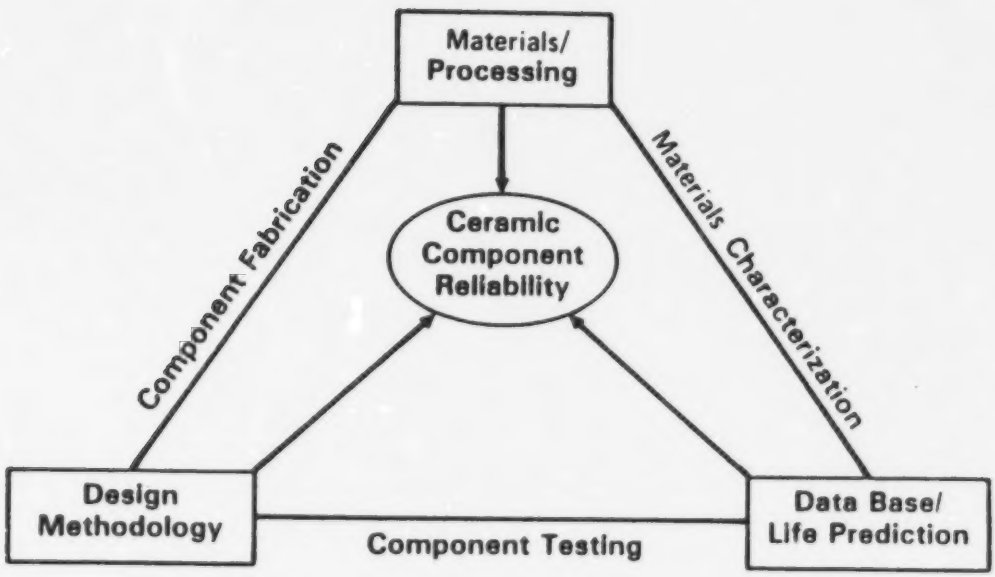


Figure 40. Relationship of Major Work Elements to Ceramic Component Reliability

9. SUMMARY AND CONCLUSIONS

9.1 Summary

The information collected in this report re: the impact of international developments in advanced ceramics on Canadian industry can be summarized as follows:

i. Rapid global progress will occur in the development and commercialization of Advanced Ceramics

Advanced ceramics exhibit superior functional (optical, electrical, magnetic, chemical) and mechanical (wear and abrasion resistance, high temperature mechanical strength) properties and, therefore, have become indispensible to meet the technological requirements of a wide range of industries. Rapid global progress is expected to occur in their development and commercialization in the next few decades. The first source of growth arises from increased opportunities for the manufacture of advanced ceramic products. These opportunities are being used by existing ceramic manufacturers to expand their market base. In addition, new enterprises, both large and small, are being formed. The former types of enterprises are being formed by large corporations either by acquistion-vertical integration and/or by joint-venture schemes; this is particularly true in the U.S. and in W.Europe. Smaller new companies are being created by entrepreneurs.

The second source of growth can be attributed to the fact that advanced ceramic technology is an "enabling technology". The needs of high-technology industries, particularly microelectronics, communication and data processing, sensors, robotics, and for specialized materials and components is expected to catalyze growth.

The third source of growth is coming from the opportunities to improve efficiency/productivity in industrial and manufacturing sectors such as: mining and mineral beneficiation, oil & gas, pulp & paper, machinery & manufacturing, and transportation.

ii. World markets for advanced ceramics will grow at a substantial rate

Worldwide markets for advanced ceramics will increase at a rapid rate. The sales of advanced ceramics increased from US$ 905 million in 1977 to US$ 5.4 billion in 1986 - an annual growth rate of about 22 per cent. The sales are

projected to increase to US$ 12.2 and US$ 24.5 billion by the year 1991 and 1995, respectively. Japan and U.S. contributed to almost 85 per cent of the sales in 1986 and this ratio is expected to continue to the year 1995 and beyond.

Japan is the world leader at present with more than 50 per cent of the world market, and is expected to retain this ratio in the future. The sales are projected to increase from US$ 2.59 billion in 1986 to US$ 5.9 billion and US$ 12.1 billion by the years 1991 and 1995, respectively.

U.S. activities in advanced ceramics are expected to grow substantially. The sales are expected to double from US$ 2 billion in 1986 to US$ 4.5 billion by 1991 and to US$ 8.65 billion by the year 1995.

The market for advanced ceramics in Canada is expected to grow from US$ 72 million in 1986 to US$ 170 million in 1991 and to US$ 375 million by 1995.

iii. **Advanced Functional Ceramics are expected to retain their present high market share**

Presently, electroceramics constitute about 75-80 per cent of all advanced ceramics produced and form the backbone of high technology industries, particularly micro-electronics. They are expected to retain this high market share for the rest of this century. Since materials technology is keeping pace with industry needs, market performance is expected to be influenced largely by techno-economic considerations. Other areas of expected growth are: sensors, opto-electronics, and biomaterials.

iv. **The use of advanced structural ceramics is expected to increase significantly**

To date, the growth in the use of advanced structural ceramics is below projected high rates largely due to technology/cost problems associated with the manufacture of heat engine components. There is now a growing consensus that significant growth in the heat engine market is atleast a decade away; and that development of non-engine applications offer two immediate advantages. Firstly, they provide market opportunities for the first generation materials that have been developed; and, secondly, the use of these materials will contribute to improvements in efficiency and productivity in many industrial sectors. Nevertheless, the ultimate goal of all present R&D efforts

is to develop materials and materials technology for the heat engine market.

The biggest growth areas for monolithic advanced structural ceramics, in the short term (5-10 years), are expected to be cutting tools, abrasion/wear/corrosion/heat resistant parts, and heat exchangers. In the longer term i.e., beyond 10 years, significant heat engine applications are expected to be in place.

Advanced ceramic coatings for structural applications have already gained market acceptance because they can be used to improve the performance of existing metal components in uses requiring better wear/abrasion/corrosion properties. Growth rate for coatings technology is projected to be high: 28 per cent for heat engine applications, 18 per cent for marine equipment applications, and 15 per cent for chemical processing equipment.

v. International developments are expected to impact on Canadian industry

There is intense international competition to develop and commercialize advanced ceramics, particularly in Japan, U.S., and W.Europe. From a Canadian perspective, the developments in the U.S. are perhaps the most significant because of the close interaction between Canadian and U.S. economies. The government-industry commitments in the U.S. are expected to result in a rapid growth, both in the manufacture of advanced ceramics and their use by industry - specifically in the non-engine industrial sectors to gain efficiency and productivity benefits. These developments are expected to impact on the competitive position of Canadian industry vis-a-vis U.S. industry. This is particularly critical because of the impending Canada-U.S. free trade agreement.

vi. Canadian resource and manufacturing industries are aware of the impact of advanced ceramics

The Canadian resource and manufacturing industry is aware of the benefits to be accrued by the use of advanced ceramics in improving their international competitive position. The Mining and Mineral Processing industry, Pulp & Paper industry, Oil & Gas and Petrochemical industry, and the Machinery and Equipment industry have shown keen interest in participating in national efforts to develop technology capabilities in cooperation with Canadian advanced ceramics manufacturers.

vii. **Canada has a small but significant advanced ceramics industry**

Advanced ceramics industry in Canada, although relatively small, is active both in the manufacture of a number of products and in R&D aimed at developing new products and processes. These activities comprise all four important areas: advanced ceramic powders, advanced functional ceramics, advanced structural ceramics, and advanced ceramic coatings. With the exception of two large companies, most of the companies are relatively small. Most of them have good technology base and R&D capabilities. Many of them have well established product lines and market their products throughout the world.

viii. **Canada has a well established R & D base in advanced ceramics**

Canada has a significant and well established "science and technology" culture related to advanced ceramics which is internationally known. Extensive R&D capabilities and facilities are available in Canadian universities, federal government laboratories, provincial research organizations, Crown corporations and industry.

ix. **Canadian industries have shown keen interest in the development and use of advanced ceramics**

Canadian industries have shown keen interest in the industrial development and use of advanced ceramics. This interest is reflected in the formation of new industrial associations, specifically: Advanced Materials Technology Unit at Queen's University, the Canadian University-Industry Council on Advanced Ceramics, and the Canadian Advanced Industrial Materials Forum.

9.2 Conclusions

Based on the findings of this report, the following conclusions can be drawn re: impact of international developments in advanced ceramics.

a. **World markets for advanced ceramics are expected to grow substantially**

World markets for advanced ceramics are expected to grow substantially in the next two decades to meet industrial demand. The annual growth rates for both advanced functional ceramics and advanced structural ceramics are projected to be in the 20-30 per cent range. Advanced functional ceramics are expected to retain their present 75-80 per cent market share of all advanced ceramics.

b. **Intense international competition exists to benefit from increasing world markets for advanced ceramics**

Japan is acknowledged to be the world leader at present in technology, production and commercialization. Presently, it accounts for about 50 per cent of world markets and is expected to maintain this market share for the rest of this century and beyond.

U.S. is acknowledged to be the world leader in the science of ceramics. It is second behind Japan in world market share accounting for about 37 per cent. U.S. industry (with government support) has mounted intense efforts to increase its market share.

W.Germany, France, United Kingdom and other W.European countries are also intensifying their efforts to increase their present 13 per cent market share, with substantial support from their respective governments as well as from EEC.

c. **National technical resources are used to gain international competitive position**

All the industrialized countries, especially Japan, U.S., France, and W.Germany are harnessing all their national technological resources (in government laboratories, universities) to asist industry to improve its competitive position.

In Japan, MITI laboratories are used, to assist industry as part of the national program.

In the U.S., the capabilties of the government laboratories (e.g., Oak Ridge, Argonne, Brookhaven, Lawrence-Livermore, NASA, and Defence Department laboratories) are utilized to support industry in the development and commercialization of advanced ceramics.

In W.Germany, the government laboratories (DFVLR) and other national institutes (e.g., Max Planck, Fraunhoffer) are used in support of industry.

In France, government laboratories (CNRS) are used to support industry efforts.

d. **International developments in advanced ceramics will impact on Canadian industry**

International developments in advanced ceramics are expected to impact on Canadian industry in three ways:

- Canadian high-tech industries will require new advanced ceramics to maintain and improve their international international competitive position;

- Canadian resource and manufacturing industry will require new advanced ceramics to maintain and improve their international competitive position; and,

- Canadian manufacturers of advanced ceramics can benefit by participating in the growing domestic as well as international markets.

e. **Canadian high-tech industry needs can be met partially by domestic advanced ceramics manufacturers**

Bulk of the needs of high-tech industry are electroceramics. Canada already has a good industry base in electroceramics, and can expand to meet increased demands. Since the market is already dominated by large international companies, Canadian manufacturers can benefit only by participating in specialized "niche" markets.

f. **Canadian resource and manufacturing industry needs can be met by domestic manufacturers**

The recognition that efficiency and productivity of operations in the resource and manufacturing industry can be improved by the use of advanced ceramics is relatively new. Established large international companies are expanding their efforts to service this sector.

"Niche" opprtunties, however, exist for Canadian manufacturers.

g. **Canadian industry base and established R&D capabilities in advanced ceramics can be harnessed to meet both domestic and international market needs**

Canada has a small but good industry base in the production of advanced ceramic powders, functional ceramics, structural ceramics, and ceramic coatings. This could be expanded.

Canada has internationally recognized scientific capabilities in universities which could be tapped to provide industry with direct technical assistance as well as trained manpower.

Canada has extensive expertise and capabilities in government laboratories, provincial research organizations, and Crown corporations which could be beneficially used to assist both the manufacturers and users of advanced ceramics.

h. **Constraints to development must be overcome**

The major constraints that face Canadian industry are:

(i) Relatively small ceramic industry base: The industry base is small. With the exception of a few large/medium size companies, the industry is characterized by a large number of small companies. Hence, industry cannot support large-scale operations and must be very selective in identifying and implementing new "niche" opportunities. This is an inherent drawback associated with Canadian socio-economic scene and cannot be easily resolved. On the other hand, large multinational corporations cannot address small "niche" markets. Canadian companies can do well in these areas.

(ii) Relatively small R&D base: Canada has very a good R&D base, however, it is relatively small compared to total international effort. Hence, it must implement two strategies:

- It must be selective in the identification and development of technologies.

- It must harness all the technological resources, in industry, in universities, in government laboratories, provincial research associations, and in Crown corporations.

(iii) Technology availability: Advanced ceramics have been under development for almost 15 years in Japan and in the U.S. Over this period considerable technology has been developed. Because of time/cost considerations, Canadian companies have to rely on "technology transfer" mechanisms to catch up with international competition.

(iv) Technology awareness in Canadian industry: Technology awareness is a particularly serious problem in Canada. Technology development is taking place at a very fast pace in other countries and Canadian industry is falling behind. This applies both to the ceramics manufacturers and the user industries, particularly resource and manufacturing sectors.

(v) Product development expensive: Product development in the advanced ceramics industry is very expensive. Most of the Canadian companies currently, or potentially, involved in advanced ceramics are too small to be able to finance major product development without significant government support.

(vi) Low level of scientists/engineers in industry: More than 70 per cent of Canadian manufacturing firms do not employ full-time scientists and/or engineers. In many instances, the firms cannot justify the hiring costs even if they realize the need.

(vii) Lack of laboratory-pilot plant infrastructure: At present there in no infrastructure to provide laboratory-pilot plant back up to assist industry in the commercialization of processes developed in university-industry cooperative programs. This is particularly true in the case of small ceramic manufacturing companies. An equally important need exists for providing laboratory-pilot plant infrastructure to assist the user industries to evaluate the performance of advanced ceramics.

(viii) R&D funding is limited: At present, the bulk of the R&D support to industry comes through the NRC-IRAP programs. The new NRC-IRAP programs designed to promote industrial consortia in advanced ceramics is a positive development. Other departments (e.g., EMR and DRIE) should consider R&D support programs related to their missions.

10. RECOMMENDATIONS

There seems to be no doubt that Canadian industry will benefit significantly by repsonding to the opportunities provided by advanced ceramics. Industry, by itself, is not expected to take full advantage of these opportunities because some of the associated problems that have to be overcome are too wide in scope and beyond the capabilities of even the big companies. It is believed that government can catalyze industry mobilization by implementing the following recommendations.

i. Government should provide leadership

The government has already selected Advanced Industrial Materials - which include advanced ceramics - as a strategic technology. Both the Ministry of State for Science and Technology (MOSST) and the Department of Regional Industrial Expansion (DRIE) have taken initiatives to promote advanced ceramics. These initiatives are expected to contribute significantly towards the manufacture, use, and export of advanced ceramics products.

To maximize the benefits to the Canadian economy, however, it is necessary to bring the federal government laboratories into play for reasons outlined below:

ii. The expertise, capabilities, and facilities available in the federal government laboratories should be harnessed in support of Canadian industry needs in advanced ceramics

Canadian industry needs support in the following areas:

- Technology development & utilization
- Technology awarness
- International and national linkage and technology transfer

Established technology, expertise, capabilities and facilities exist in the federal government laboratories, particularly the National Reserach Council (NRC) and the Department of Energy, Mines, and Resources (CANMET). These should be harnessed to assist Canadian industry.

ii. **Expand and promote industry-linkage**

The cost-effectiveness and industry-benefits of science/technology development activities in government laboratories can be enhanced significantly and maximized by expanding and promoting linkage with industry. The industry linkage can take the form of various joint and collaborative programs and services.

a. Collaborative programs

- Promote and participate in multi-client studies;
- Promote and participate in industry consortia; and,
- Expand industry secondments.

These programs can be designed to achieve partial cost recovery.

b. Free services

- Provide "technology awareness/diffusion" to industry by initiating and/or participating in activities designed to transfer technology.
- Promote and/or provide international and national technology linkages and technology transfer to industry.

iii. **Provide management structure required to effectively implement industry-linkage programs**

The success of the the proposed industry-linkage programs depends upon the effectiveness with which commitments to industry are delivered. Hence, it is necessary to evaluate the management structure that prevails and implement necessary changes, if warrented.

iv. **Support and use existing industry associations as vehicles to implement industry-linkage programs**

At present, there are three industry associations which relate to ceramics. They are: The Canadian University-Industry Council on Advanced Ceramics; the Canadian Ceramic Society; and the Canadian Advanced Industrial Materials Forum. All these three organizations could be used in implementing and promoting the industry-linkage programs.

The Canadian University-Industry Council on Advanced Ceramics (CUICAC) is a particularly useful organization. CUICAC was established as a joint effort of Canadian industry and universities and is designed to harness and bring together the scientific/technical capabilities of Canadian universities to assist industry. With a membership of 58 - representing universities (11), industrial companies (44), venture capital (1), and government departments/ agencies (2), CUICAC already provides services to its members in a number of areas, specifically: "Technology Awarness" through Workshops and Newsletters; "Technology Development and Exploitation" by promoting industrial consortia; and "International Linkage" by forging cooperative relationships with industrial associations in foreign countries (such as Japan Fine Ceramics Association).

CUICAC is planning to set up a "National Network" on advanced ceramics comprising Canadian industry, universities, provincial research organizations, federal government laboratories and crown corporations. This initiative is unique and timely and could be used to enhance the recommended industry-linkage programs.

v. Initiate and organize consortia to assist Mining & Mineral Beneficiation and Pulp & Paper Industries

Information generated in this study suggests that the Canadian Mining & Mineral Beneficiation Industry as well as the Pulp & Paper Industry is looking for a suitable R&D infrastructure to evaluate the use of advanced ceramics to improve productivity/efficiency of operations. The The government laboratories have an unique opportunity to play an active role in establishing and technologically supporting these consortia, particularly in providing pilot plant facilities.

Appendix 1

BIBLIOGRAPHY

1. Kingery, W.D., Bowen, H.K., and Uhlmann, D.R. — Introduction to Ceramics 2nd Edition, John Wiley & Sons, Inc New York, N.Y. 1976

2. Burke, J.J. Gorum, A.E., and Katz, R.N. (Editors) — Ceramics for High-Performance Applications Brook Hill Publishing Company 1974

3. Lenoe, M.L. Katz, R.N., and Burke, J.J. (Editors) — Ceramics for High-Performance Applications: III Reliability Plenum Press, New York 1983

4. Riley, F.L. (Editor) — Progress in Nitrogen Ceramics Martinus Nijhoff Publishers, 1983

5. Somiya, S. (Editor) — Ceramic Science and Technology at the Present and in the Future Uchida Rokakuho Pub, Co.Ltd Tokyo, Japan, 1981

6. Hench,L.L., and Ulrich, D.R. (Editors) — Ultrastructure Processing of Ceramics Glasses, and Composites John Wiley & Sons, Inc. 1984

7. Onada, G.Y., and Hench, L.L. (Editors) — Ceramic Processing Before Firing John Wiley & Sons, Inc. 1978

8. Heuer, A.H., and Hobbs, L.W. (Editors) — Science and Technology of Zirconia Advanced in Ceramics - Volume 3 The American Ceramic Society, Inc 1981

9. Kenny, G.B., and Bowen, H.K. — High-Tech Ceramics in Japan: Current and Future Markets Bul.Am.Ceram.Soc., 62 (5) 590 (1983)

10. McLean, A.F. — Ceramic Technology for Automotive Turbines Bul.Am.Ceram.Soc.,61 (8) 861 (1982)

11. Iwata, S. — R&D on High Technology Ceramics in Japanese Industries Bul.Am.Ceram.Soc.,61 (9) 926 (1982)

12. Yanagida, H., and Koizumi, M.
Major Ceramic Research Programs Sponsored by the Japanese Government
Bul.Am.Ceram.Soc., 61 (9) 929 (1982)

13. Fukunga, O., and Morisyoshi, Y.
Research at Japanese National Laboratories
Bul.Am.Ceram.Soc., 61 (9) 923 (1982)

14. Bowen, H.K., and Pask, J.A.
Learning from Japan's Developments in High Technology Ceramics
Bul.Am.Ceram.Soc., 61 (9) 916 (1982)

15. Johnson, L.R., and Teotia, A.P.S.
A Structural Ceramic Research Program: A Preliminary Economic Analysis Report
No.ANL/CNSV-38, March 1983
Argonne National Laboratory

16. U.S.Commerce Dept.
A Competitive Assessment of the U.S. Advanced Ceramics Industry. Published by U.S. Commerce Department.
P.B.84-162288, March 1984

17. Oak Ridge National Laboratory
Ceramic Technology for Advanced Heat Engines: Program Plan ORNL/TM-8896, June 1984.

18. Charles River Associates
Technical and Economic Assessment of Advanced Ceramic Materials. Study done for the National Bureau of Standards, Washington D.C.

Vol 1: Summary and Conclusions
Vol 2: A Case Study of Ceramics in Heat Engine Applications
Vol 3: A Case Study of Ceramic Capacitors
Vol 4: A Case Study of Integrated Capacitors
Vol 5: A Case Study of Ceramic Toxic and Combustible Gas Sensors
Vol 6: A Case Study of Ceramic Cutting Tools

19. Evans, A.G.
Technical and Scientific Assessment of the Reliability of Advanced Ceramics, July 1982.
(Report sponsored by the National Bureau of Standards, Washington D.C.)

20. Natl.Academy of Sciences
National Research Council
Washington D.C.
High-Technology Ceramics in Japan
1984

21. The Long-Term Credit Bank of Japan, Ltd.
Japan's High Technology Industries (2)
February 1984.

22. MITI, Japan
Report of the Working Group on Fine Ceramics and Fundamental Issues,
May 1984

23. Yano Research Institute, Ltd.
New Ceramics Market in Japan,
August 1982

24. C.M.Chirin
Advanced Industrial Materials in Japan
August 1983
(Report prepared for the Canadian Embassy, Tokyo, Japan).

25. M.K.Murthy
Advanced Ceramics
Report No.3/86
Office of Industrial Innovation
Dept.Regional Induistrial Expansion
Ottawa. 1986

26. J.C.Agarwal
Process Economics and Strategies in the Advanced Ceramics Industry
Advanced Ceramic Materials
Vol 1, No 4, p 332, 1986

27. IBI Inc, Tokyo
Advanced Ceramics in Japan: Market Trends and Industry Structure. 1987
(Prepared for the Canadian Embassy Tokyo)

28. Industrial Bank of Japan
Light and Shadow: The two aspects of the New Materials Business
(A special report of IBJ, 1986)

29. Japan Fine Ceramics Association
Fine Ceramics for Future Creation
Annual Report for Overseas Readers
1985

30. Japan Fine Ceramics Association
Fine Ceramics for Future Creation
Annual Report for Overseas Readers
1986

31. Japan External Trade Organization	The Development of Structural Fine Ceramics in Japan Special Issue No. 15. 1983
32. Fisher, G.	Input Needed for Census Accuracy Bul.Am.Ceram.Soc., 67 (1) 57 (1988) Electronics Products Weathering Market Swings Bul.Am.Ceram.Soc., 66 $4) 636 1987)
33. A.T.Kearny International, Inc., Tokyo, Japan	International Market Research Profile of Advanced Industrial Fine Ceramics: Japan. Report prepared for U.S.Commerce Department
34. ProPlan, London. U.K.	Profile of U.K.Market for Advanced Industrial Fine Ceramics. Report prepared for the U.S.Commerce Department. (Bul.Am.Ceram.Soc., 67 (1) 59 (1988)
35. Frost & Sullivan	Advanced Ceramics in Europe: 2.2 Billion Market by 1992 Ceramics Industry.p 16, Jan 1988
36. Abraham, T	Advanced Structural Ceramics Market Study Report from Business Communications Co, Inc. (BCC), Norwalk, Connectcut. (Cer.Industry p10, Jan 1988)
37. Alliegro, R.A.	Ceramic Application and Design Ceramic Industry p(s2) February 1988
38. Block, R.	CPS Microengineers: New Breed of Materials Ceramic Industry p51, April 1988
39. Int'l Resource and Development Inc.	Advanced Ceramics Market Opportunities Report. Bul.Am.Ceram.Soc., 66. No 4 640 (1987)
40. Schober, M.	Ceramics Thrive in Changing World Markets. Bul.Am.Ceram.Soc., 66 (12) 1698 (1987)

41. J.Nantel — Challenges and Uses for Advanced Ceramics in the Mining Industry. Paper presented at the 6th CUICAC Workshop, Toronto, Feb 25-26, 1988

42. M.Sayer — Applications of Advanced Materials in the Mining Industry: Vol 1. Report prepared by Advanced Materials Technology Unit, Queens University, Kingston, Ontario for Hard Rock Mining Research Limited. June 30, 1987

43. Newnham, R.E. — The Golden Age of Electroceramics Advanced Ceramic Materials Vol 3, No 1, P 12, 1988

44. Yanagida, H. — Industrial and Cultural Revolution Through High-Tech Ceramics Advanced Ceramic Materials Vol 2, No 1, p 31, 1987

45. Hench, L.L. — Ceramic Implants in Humans Advanced Ceramic Materials Vol 1, No 4, p 306, 1986

46. K.K.Chan and J.B.Wachtman — Expanding World of Ceramic Coatings Ceramic Industry p 24, September 1987

47. Lackey, W.J. Stinton, D.P. and Fehrenbacher, L.L. — Ceramic Coatings for Advanced Heat Engines- A Review and Projection Advanced Ceramic Materials Vol 2, No 1, p 24, 1987

48. Rothman, E.P. Clark, J.P. and Bowen, H.K. — Cost Modelling of Structural Ceramics Advanced Ceramic Materials Vol 2, No 1, p 34, 1987

Ceramic Cutting Tools: A Production Cost Model and an Analysis of Potential Demand Advanced Ceramic Materials Vol 1, No 4, p 325, 1986

49. Taguchi, M — Applications of High-Technology Ceramics in Japanese Automobiles Advanced Ceramic Materials Vol 2, No 4, p 754, 1987

Appendix 2

List of Persons who Participated in Discussions

No.	Name	Organization
1.	B.C.H.Steele	Imperial College of Science & Technology London, U.K.
2.	J.B.Wachtman	Center for Ceramics Research State University of New Jersey Piscataway, NJ, USA
3.	R.M.Sprigs	The New York State College of Ceramics Alfred, NY, USA
4.	T.J.Whalen	Ford Motor Company Scientific Laboratory Dearborn, Michicagn, USA
5.	P.A.Verhey	Williams & Wilson Ltd Toronto, Ontario
6.	R.Webb	Alcan Aluminum Ltd Montreal, Quebec
7.	Kamal El Assal	Almax Industries Limited Lindsay, Ontario
8.	S.E.Prasad	B.M. Hi-Tech Inc Collingwood, Ontario
9.	A.R.Steele	Cancarb Limited Vancouver, B.C.
10.	R.Sood	Ceramics Kingston Inc Kingston, Ontario
11.	R.F.Redden	Crystar Research Inc Victoria, B.C.
12.	D.Nguyen	Datco Technology Limited Burlington, Ontario
13.	F.Rea	Edo Canada Ltd Calgary, Alberta
14.	S.Das Gupta	Electrofuel Manufacturing Co Ltd Toronto, Ontario
15.	Kamal El Assal	EYC Industries Limited Lindsay, Ontario

16. R.G.Robb	Hamilton Porcelains Limited Brantford, Ontario
17. S.A.Manktelow	Hard Materials Research Inc Mississauga, Ontario
18. J.A.E.Bell	Inco Limited Mississauga, Ontario
19. H.J.Lawrence	Industrial Ceramics Limited Mississauga, Ontario
20. D.C.Radford	JaCoat Company Kingston, Ontario
21. S.Johar	Jay-Em Ceramics Brampton, Ontario
22. G.W.Roland	Kennametal Ltd Toronto, Ontario
23. A.J.Ankus	Lakeside Electronics Ltd Whitby, Ontario
24. J.D.Morris	Macro Division of Kennametal Inc Port Coquitlam, B.C.
25. C.Bigonesse	Metal 7 Inc Sept-Isles, Quebec
26. P.Kalisky	Montreal Carbide Co. Ltd Montreal, Quebec
27. A.Bajsarowicz	MPB Technologies Inc Dorval, Quebec
28. M.Blamire	Murata Erie N.A. Ltd Kingston, Ontario
29. R.Lang	Neosid (Canada) Limited Toronto, Ontario
30. D.Herscovitch	Noranda Research Centre Point Claire, Quebec
31. P.Duncker	Northern Pigment Co Toronto, Ontario

32. K.P.Fellinger	Norton Advanced Ceramics Canada Inc Niagara Falls, Ontario
33. C.J.Simpson	Ontari Hydro Research Division Toronto, Ontario
34. M.Sikich	Peacock Inc Mississauga, Ontario
35. J.W.H.Blott	Plasma & Flame Coatings Ltd Winnipeg, Manitoba
36. A.Dubreuil	Polyceram Inc Montreal, Quebec
37. A.Pekarasky	Powerplex Technologies Inc Downsview, Ontario
38. J.Kelly	Quality Hermetics Company Toronto, Ontario
39. M.A.Clegg	Sherritt Gordon Mines Ltd Fort Saskatchewan, Alberta
40. B.R.Junkin	Standard Aero Limited Winnipeg, Manitoba
41. L.Gosselin	Vac-Aero International Inc St. Laurent, Quebec
42. W.Wittie	Witteck Development Inc Mississauga, Ontario
43. C.Thompson	Pulp & Paper Research Institute Point Claire, Quebec
44. M.F.Bell	Concordia University Montreal, Quebec
45. D.W.Jones	Dalhousie University Halifax, N.S.
46. M.Rigaud	Ecole Polytechnique Montreal, Quebec
47. R.Angers	Laval University Ste-Foy, Quebec

48. R.A.L.Drew	McGill University Montreal, Quebec
49. P.S.Nicholson	McMaster University Hamilton, Ontario
50. M.Sayer	Queen's University Kingston, Ontario
51. B.K.Mukherjee	Royal Military College of Canada Kingston, Ontario
52. H.W.King	Technical University of Nova Scotia Halifax, N.S.
53. A.C.D.Chaklader	University of British Columbia Vancouver, B.C.
54. C.Roy	University of Sherbrooke Sherbrooke, Quebec
55. J.M.Toguri	University of Toronto Toronto, Ontario
56. D.E.Brodie	University of Waterloo Kitchner, Ontario
57. H.Yamauchi	University of Windsor Windsor, Ontario
58. B.Palmer	Atomic Energy of Canada Limited Chalk River, Ontario
59. T.A.Wheat	Dept.Energy, Mines, & Resources(CANMET) Ottawa, Ontario
60. D.Vineot	Defence Research Establishment Atlantic Halifax, N.S.
61. J.R.Wright	National Research Council (ARL) Halifax, N.S.
62. R.B.Heimann	Alberta Research Council Edmonton, Alberta
63. K.N.Tandon	Manitoba Research Council Winnipeg, Manitoba

64. R.F.MacNeill	Nova Scotia Research Council Halifax, N.S.
65. I.H.Joyce	Ontario Research Foundation Sheridan Park, Ontario
66. J.Cameron	Advanced Materials Technology Unit Queen's University Kingston, Ontario
67. J.E.Lockyer	Canadian Advanced Industrial Materials Forum Toronto, Ontario
68. L.L.Taylor	Canadian Ceramic Society Toronto, Ontario
69. P.S.Nicholson	Canadian University-Industry Council on Advanced Ceramics Hamilton, Ontario
70. J.P.McGeer	Ontario Centre for Materials Research Kingston, Ontario